A System Design Framework for the Transnet Engineering (TE) Product Development Coaches (PDC) Business as an Original Equipment Manufacturer (OEM) of Railway Coaches

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CANDIDATE'S DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

A study was carried out to investigate the different design failure factors within the Transnet Engineering (TE): Product Development Coaches (PDC) environment. TE: PDC is responsible for the design and development of new passenger railway coaches. System failure, whether it be the failure to meet the completion criterion (e.g. time, cost, quality and stakeholder requirements validation) and/or the stakeholder satisfaction, may lead to the compromise of organisational reputation and inefficient use of organisation capital.

The purpose of the research was to develop a *System Design Framework*, and from it derive the *System Design Process* which could potentially be used by TE: PDC to mitigate system failures, by applying different Systems Engineering principles and concepts. The different design failure factors were identified through literature review, archived company data and semi-structured interviews. The *System Design Framework* and *Process* were further evaluated by a panel of experts through a focus group.

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CHAPTER 1

1 *INTRODUCTION*

This section discusses the context, background and rationale for conducting this research. The research is focused within the Transnet Engineering (TE) environment, which is one of Transnet's Operating Divisions (OD's). TE provides services such as advanced manufacturing, maintenance, and refurbishment of rolling stock and specialised equipment to other Transnet ODs and external clients (Transnet (2018)). A holistic system view is taken to give concept to the application area as well as the problem area. This includes the definition of the system of interests, its elements and the interaction amongst themselves, its environment and other enabling systems is taken to. The critical research question, as well as the objectives of the study, are discussed.

1.1 Research Background and Context

To give context to the environment of application as well as the subject of the study, the Viable System Model (VSM) of Beer (1989) is used to describe TE's organisational structure. The model provides a framework for designing flexible, adaptable organisations that balance external and internal perspective, and long- and short-term thinking (Espejo *et. al*. (1997)). The model was adapted for the study and is represented by *Figure 1*.

TE's ambition is to strengthen its rolling stock capability by taking the next step of becoming an Original Equipment Manufacturer (OEM) of rolling stock and logistics equipment and driving the Transnet 4.0 strategy. The Transnet 4.0 strategy aims to reposition Transnet in the technology-driven industrial revolution focusing on three main areas of growth i.e. Geographic expansion, product and service innovation and expanding the scope of Transnet's manufacturing business. As a result, TE is strategically positioning itself by restructuring its sub-divisions, with one of its products being Product Development (PD) businesses(Transnet Engineering (2018), Transnet (2018)). TE: PDC business is the System of Interest (SoI) for this study i.e. the scope of the study is limited to the TE: PDC environment. It forms part of *System 1/ Operations*, whose primary activity is to manufacture and maintain a variety of passenger coaches from mainline to suburban coaches. TE: PDC functions in an existing current environment (Country X) with the aim to expand its footprint in Africa as part of its Transnet 4.0 strategy (Transnet (2018)).

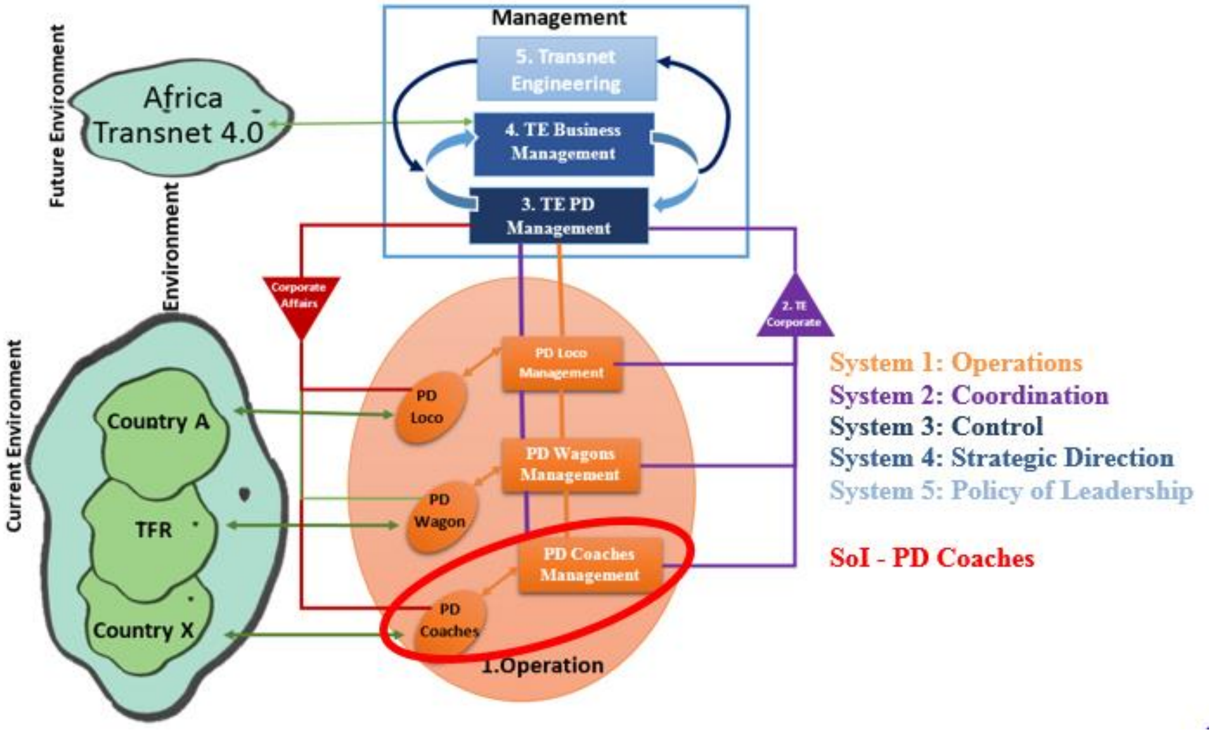

Figure 1: The Viable System Model for Transnet Engineering
Source: Author (Adapted from Beer (1989))

It is important to make the following distinction which is relevant for this study. In this study, the following applies;

Created system: Is the deliverable product i.e. New coaches

Creating system: Is a collection of people, processes, and facilities organised together to achieve a common goal of designing and developing new products (i.e. PD Coaches); which is the study of interest.

The transitioning of TE from a maintenance organisation into an OEM requires the shift in strategies, goals and the processes involved in arranging resources to achieve the organisational goals and mitigate project failure to increase its chances of a positive return on investment (Transnet Engineering (2018)). This research focused on the design processes followed in TE: PDC business when building coaches and how it has shifted to accommodate the transition, taking into consideration the effect of other product development phases in the lifecycle of the product.

1.2 Purpose of the Study

The aim of the research is to develop a *System Design Framework* for the Transnet Engineering: Product Development Coaches (i.e. TE: PDC) business as an OEM; to inform project success, drawing on success and failure of other rolling stock projects (both freight and passenger), as well as other OEMs in the transportation industry.

The purpose of the *System Design Framework* would be to address issues relating to the *creating system's* (i.e. TE: PDC) design process, that occur throughout the *created system's* (i.e. New coaches) lifecycle which may have an influence project failure. The framework draws on various existing architectural and enterprise frameworks, as well as system design methodologies and tools. The development of the *System Design Framework* is aimed at ensuring that project success is defined and achieved from considering different stakeholders' perspectives. A *System Design Process* is derived from the framework for process guidance during the development of new products within PDC.

1.3 Problem Statement

As part of TE's intentions of becoming an OEM and expanding its advanced manufacturing business, TE: PDC is expected to develop new products (Transnet Engineering (2018)). According to Youker (2017) projects that require the development of new products have a high degree of uncertainty, increasing the chances of project failure. Transnet currently implements the Project Lifecycle Process (PLP) shown below, when executing their projects.

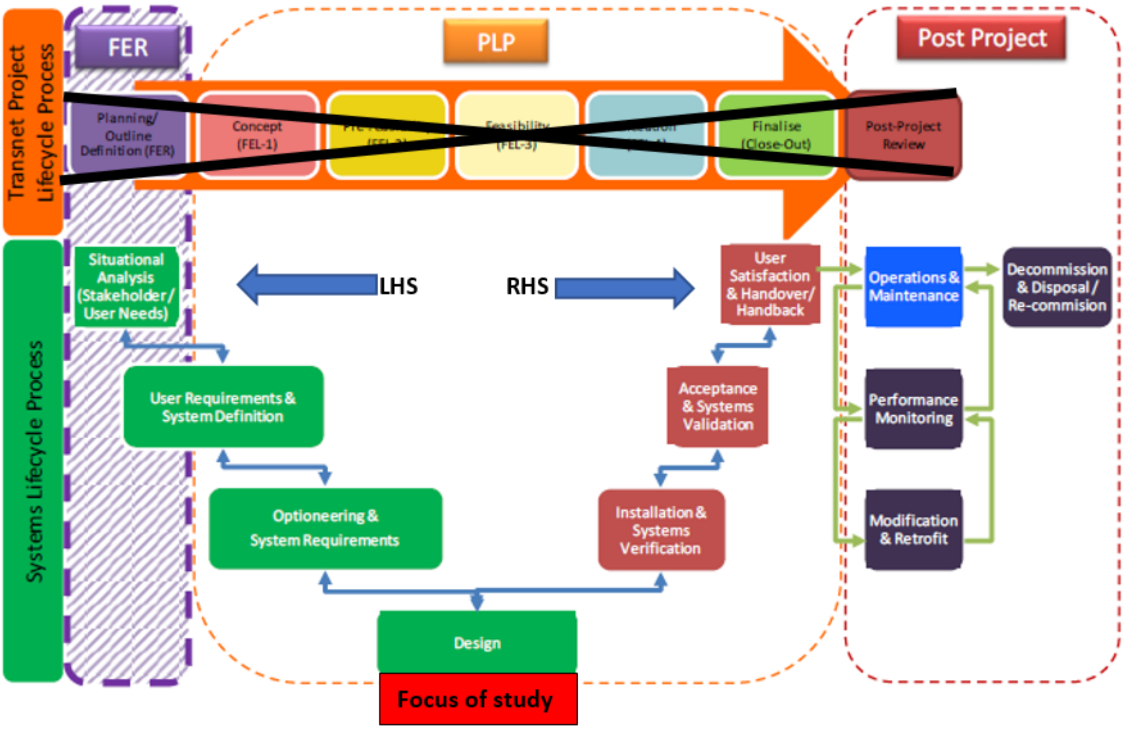

Figure 2: System lifecycle process as adopted by Transnet showing the author's interpretation
Source: Author (Adapted from (Transnet Capital Projects (2008) and *ISO/IEC/IEEE15288 (2015)*)

The Transnet PLP was developed by Transnet Capital Projects (TCP) to suit large capital projects, mostly of civil/infrastructure nature, drawing on best practices as applied to progressive project phases

(Transnet Capital Projects (2008)). According to the Transnet lifecycle process, the detail design phase is covered in the PLP (Transnet Capital Projects). However, the current PLP is deficient as it was not set up to address electro-mechanical OEM/Design type projects. The following deficiencies identified:

- PLP is designed for use in mega-projects (i.e. Projects costing more than US$15m). However, PDC is not involved in projects of such magnitude.
- PLP does not consider the technical processes of the system lifecycle process which is necessary for design type projects.
- PLP is focused on the project domain rather than on the system domain.

Furthermore, the products produced by TE: PDC have been questioned in the past based on their quality, completeness as well as delivery time (Mokwena *et. al.,* (2016)). It is thus important to consider factors that might have led to such results, of which design processes might be one of them. This research focuses on the adaptation of systems approaches and methodologies for the design process as a plausible practice to mitigate project failure at TE: PDC. TE: PDC currently uses its internally developed Product Design and Development Process (PDDP). However, the process documented;

- Does not involve all stakeholders in the early stages,
- Has no formal phase gates to review and close off phases,
- Between URS and conceptual design phases:
  - The PDDP has no system requirements specified,
  - The PDDP has no stakeholder involvement (Design concepts solely performed by PDC designers),
- Has no planning at the early stages of the PDDP for:
  - Verification and validation
  - Maintainability, Reliability, Availability and Safety
  - Production (Manufacturability)
  - Hand over
  - Decomposition etc.

The problem statement for the research is as follows:
Transnet Engineering (TE) Product Development Coaches (PDC) business experience as an OEM is insufficient as it is a relatively new business; and also constrained by its inefficient use of resources such as time, capital and manpower. This results in a higher probability of project failure when considering the whole lifecycle as an OEM (Madzibane (2018), Transnet Engineering (2018)).

1.4 Research Motivation

The change from maintenance based to OEM organisation requires changes in the processes carried out by TE: PDC. Over and above that, TE: PDC will execute more similar projects in the near future (Transnet_Engineering (2018)). Thus, a more holistic approach to problem definition and problem-solving is required to be taken.

1.5 Research Question

How can *systems design principles* and *methodologies* be used to develop a *System Design Framework* to mitigate the *failure* of *design projects* in TE: PDC as an *OEM* organisation?

Sub-questions:

- What factors contribute to a *system design failure* in *OEM organisations* in the *transport sector* e.g. railway, road and aviation?
- How would a formalised *System Design Framework* mitigate the risk of through lifecycle *failures for TE: PDC as an OEM?*

1.6 Research Objectives

The objectives of this research are to:

- Evaluate factors affecting the performance of OEM design projects throughout the lifecycle.
- Develop a *System Design Framework* for the development of coaches in TE as an OEM.
- Verify the use of the framework to develop the final *System Design Framework*.

1.7 Outline of Chapters

The outline of the report is represented graphically for better visualization. Firstly, a review of the literature was conducted and documented to identify the problem in CHAPTER 2. Through different tools which were thoroughly described in CHAPTER 3, data were collected, and analysis is presented in CHAPTER 4; and the *System Design Framework* and *Process* were developed. To complete the study, CHAPTER 5 frames the project by providing a brief discussion and future recommendation of the study. See below for the layout of the chapters.

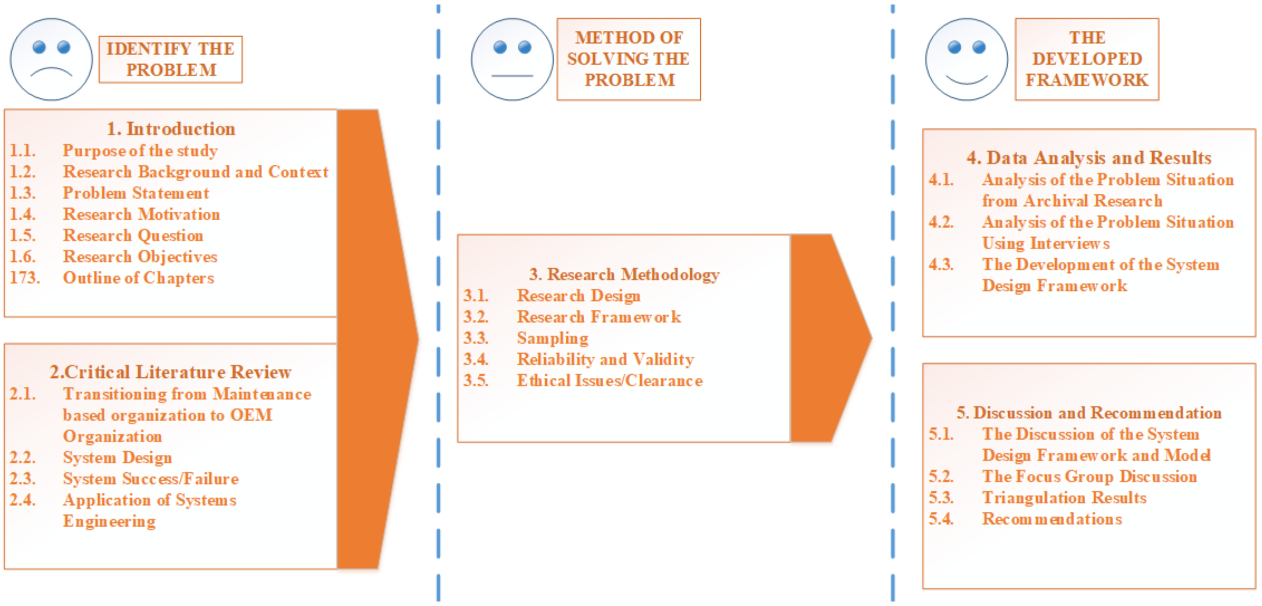

Figure 3: The outline of the report
Source: Author

CHAPTER 2

2 CRITICAL LITERATURE REVIEW

The below subsections were the key focus areas of critical literature review. They are extracts from the title of the study "*A System Design Framework for the Transnet Engineering (TE) Product Development Coaches (PDC) Business as an Original Equipment Manufacturer (OEM) of Railway Coaches*".
Critical literature review was used to highlight the concepts used, the context, and the interrelation of the subtopics and their contribution towards the development of the *System Design Framework* and *Process*.

System design is the process of determining the overall system architecture, including modules, interfaces, physical processes etc., that will satisfy the system's essential requirements (Dennist *et. al.* (2012)). It is one of the fundamental phases of system lifecycle or System Development LifeCycle or SDLC (ISO/IEC/IEEE15288 (2015)). It is thus difficult to exclude the concept of a lifecycle from the framework as it is mutually exclusive system design; further raising the importance of discussing the concept of SDLC. This is elaborated further in the below sections.

2.1 Transitioning from Maintenance based organization to OEM Organization

2.1.1 Maintenance vs. OEM organisation

An organisational structure refers to the manner in which various parts of an organisation are formally arranged to meet organisational goals (Haroun *et. al*., (2009)). This section presents the difference between an OEM or Original Equipment Manufacturer and a Maintenance organisation's organisational structures and summarises them in the below table.

Table 1: Maintenance vs. OEM organisations

Characteristics	Maintenance Organization	OEM Organization
Purpose	Responsibility varies from one organisation to another but typically aims to keep/maintain assets in a good and safe condition for operation;	Design, develop and certification of new products. Provision of full-life technical support
Material management	Can plan for spare parts and material pre-order.	Dependent on design, cannot be pre-ordered.
Typical organisational HR structure	A larger number of craft workers than managers.	Larger middle management due to the presence of specialists.
Type of worker/ level of sophistication of work	Blue-collar – Manual labour	White-collar – Desk work
Performance and production measure	Availability of assets, mean time between failure, failure/ breakdown frequency, production rate index	Design effectiveness, quality of the product, time-released to market, design efficiency, cross-functional integration effort etc.

What ranks higher (Time, quality or cost)	Speed is critical, downtime can cost millions of Rands a day depending on the organisation.	Time to market ranks higher than cost. Quality is also important.
Example of project management process	Maintenance Management Function (MMF)	Project Management framework, stage-gate framework etc.
Turnarounds	Shorter	Longer
Degree of new technology/ technology change	Low	High
Examples of applied models	Missile maintenance, self-diagnosis, co-generation system maintenance etc.	Waterfall, Double diamond, ADDIE etc.

Source: Author (adapted from (Haroun et. al., (2009), Youker (2017)*,* Muhammad et. al., (2016) *and* Yin (2010)*)*

Transnet_Engineering (2018) defines OEM as a company that buys parts from suppliers and incorporates or re-brands these into a new product under its name. This definition is supported by the Oxford Dictionary (2019) definition which refers to OEM as an organization that makes products from components bought from other organizations. A maintenance organisation, however, focuses on providing service to enable an organization to achieve its objectives, including but not limited to keeping organisation's assets in good condition and safe to perform their intended function (Haroun *et. al.*, (2009)). There is a noticeable difference between the two types of organisations; transitioning from one to the other requires a change in processes, procedures and policies to accommodate the change. For TE, TE: PDC was the product of the transition. Part of the purpose of the study is to determine how TE changed to accommodate the transition.

2.1.2 New Product Development

According to Kundu (2015), New Product Development or NPD is the complete process of bringing a new product in the market. New products cover a range of products including original products, improved products, modified products and new brands developed through the organisation's research and development efforts (Cengiz *et. al.*, (1998)). Kundu (2015) states that NPD process involves two parallel paths i.e. idea development and marketing. Giving an idea a physical reality into which to perform its function is a task that requires NPD to be actively managed to ensure that the end product is reliable and attractive to the consumers (Kundu (2015)). The author uses the Booz Allen Hamilton (BAH) model to represent the process as seen below.

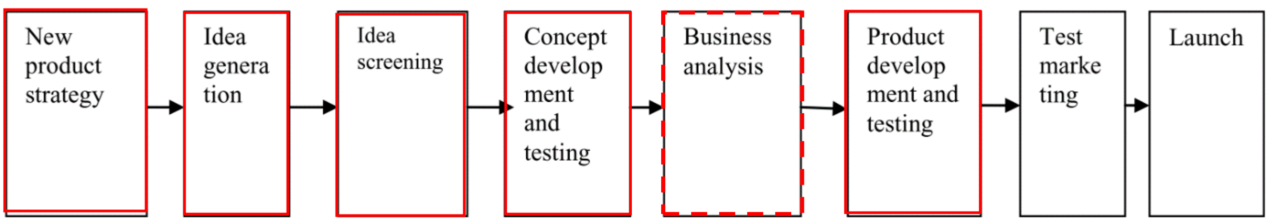

Figure 4: The Booz Allen Hamilton model of new product development highlighting the focus area for the research
Source: Author (Adapted from Kundu (2015))

Although market-related issues will have an impact on system design, the research will, however, be focused on the process of bringing the idea into existence (highlighted in the above diagram), in cognisant of "Business analysis" by analysing the effect of TE transitioning from maintenance-based company to an OEM organisation. NPD projects have some unique characteristics of their own that have the potential to increase project risk (Adcock (2017)). According to Youker (2017), new product type projects have a high degree of uncertainty and time pressure, with low stability of scope; thus, increasing chances of failure. Hence the need to investigate and determine the means of mitigating these failures.

2.1.3 TE as an OEM of coaches

Transnet Engineering has been involved in rolling stock maintenance and production; it was thus logical for TE to establish its new product in a market that was already familiar to hold a competitive advantage, taking leverage of access to market, product knowledge as well as a wealth of engineering knowledge (Transnet_Engineering (2018)). This notion is supported by Cooper *et. al*, (2010) and Ahmed *et. al*, (2015), as both authors identify lack of experience and knowledge in the field as one of the failure factors in NPD.

TE: PDC as an OEM, produces new Coaches, made from components purchased from other organizations (Transnet_Engineering (2018)). An organization needs to continuously evolve to respond to the changes in technology, processes and environment (Haroun *et. al.*, (2009). As part of its process of evolving, TE needs to align its strategies and approach to accommodate the new changes. TE has identified the two operating models within the current OEM trends to be used, i.e. modular approach and vertically integrated approach, learning from other OEM's such as Transmesholdings, China South Rail (CSR) as well as China North Rail (CNR) (Transnet_Engineering (2018)). Cengiz *et. al.*, (1998) identifies three distinct categories of NPD i.e. Innovative products that satisfy the unsatisfied needs; replacement products that are significantly different from existing ones; and imitative products which are new to the organization but not new to customers. The last two definitions apply to TE: PDC.

2.2 System Design

According to ISO/IEC/IEEE15288 (2015), "*a system is a combination of interacting elements organised to achieve one or more stated purposes*"; and Wymore (1993) defines system design as a development of a model on a basis of which a real system can be built, developed or deployed that will satisfy all the specified requirements.

As explained in *section 1.1*, the term "system" can refer to either a creating or created. The system referred to in this context of the "system design" definition is the created system. It is, however, vital to keep in mind that the system of interest is the creating system i.e. TE: PDC, with the characteristics as per *Table*

1. Thus, *system design in this context is the process carried out by PDC, of creating a model/blueprint with which a coach product will be built*.

The study was focused on the design phase and assumes that the problem is well defined and documented from the earlier stages of the system lifecycle. The design phase focuses on the solution domain i.e. How to implement the solution, and it follows right after requirements analysis phase, and before the system implementation phase on the Systems Engineering process ((TutorialsPoint (2020)) and (INCOSE (2015)). However, according to Wymore (1993), the system design cycle starts much earlier in the system lifecycle. It is made up of the first three system lifecycle phases which are requirements development, concept development and full-scale engineering development. This demonstrates the mutual exclusivity of system design and system lifecycle, bringing the need to discuss the concept of a thorough lifecycle view within the design phase. To further provide a through lifecycle view to system design, the different system lifecycle development processes are discussed. This section defines system design by looking at the different design methodologies, their relevance in system/product lifecycle and providing a critique of the existing design methodology. A definition of “lifecycle design methodology” is also provided per this study.

2.2.1 System Design methodologies

Design methodology deals with the tangible procedure at the process and activity level (Tomiyama *et al.*, (2009)). To better understand the concept of system design, different design methodologies were investigated. *Table 2* below is a summary of the different lifecycle design methodologies, their definition, uses and relevance in design.

Table 2: A summary of the different design methodologies

Design Methodology		What	How	Why	When	Source
1	**Analysis Design Development Implementation and Evaluation (ADDIE)**	A method of creation of learning materials, where the design phase documents specific learning objectives, assessment instruments, exercise and content.	Identify the gap between the desired outcome and the audience's existing knowledge and skills	To develop learning platforms and obtain business results through improved performance	When solving more structured problems, or have a model that informs you how tasks should be done	PDLDPJ (2019)
2	**Design Structure Matrix (DSM)**	"A matrix representation of a system or system problems.	Focus on information flow and interdependencies between different domains to manage complexities.	Used for clustering and structuring system components.	When different problems can be solved by a similar component of a system	Tomiyama *et al.*, (2009)
3	**Agile Design**	Breaks down larger projects into small, manageable sections called interactions that are incremental with each stage of the project	Follow a short lifecycle (Planning, executing, Review, Rise and repeat), which repeats during each iteration	To accommodate the changing market (or requirements) and release product quicker	When products need to be released faster	Szalvay *et. al.*, (2004)
4	**Design Centred**	A sequential method that considers a more life-cycle consideration and the design analysis at the front end of the design stage/process	Design stage considers downstream activities by considering their requirements, and the process is centred around Computer-Aided-Design models.	To provide a method that avoids making design changes at each sequential stage as it can be expensive, as quality and cost is the driving force	When design release issues need to be controlled	Yazdan*i et. al.*, (2014)

5	**Failure Mode and Effect Analysis (FMEA)**	A systematic approach of the analysis of possible system failures for safety and resource efficiency reasons.	Identifying and eliminating any possible system failure during the product design stage.	To find a way a system can cope with such failures.	When the system is known in detail.	Tomiyama *et al.*, (2009)
6	**Top Down Design (Stepwise refinement)**	Design process that moves from a larger broader high-level design concept to a smaller, more specific and detailed lower level.	Divide the global relationship into fragments without information loss and duplicates, then define and allocate the fragments tasks.	For tasks allocation.	When there is quality information available for the fragmentation process, and quantity information for the allocation process.	Creswell (2009)
7	**Object Oriented Design Approach**	Method models a real-world process using objects (represented by actual people, transactions, things etc.) i.e. the solution is seen as a set of computations performed in the context of objects	Objects are represented by a class which consists of object properties, with internal/behaviour and external/interface definitions, then interfaced with objects of other classes to form a system.	Decouple and couple system and to enable reusability of the system	When the implementation of each part of the system can be independent and interfaces defined	Adenowo *et. al.*, (2013)
8	**Modular Design process**	Subdivides a system into smaller modules that can be used by different subsystems to enable mixing and matching of components.	Modules/components are designed independently, then integrates to function as a whole (Decomposition and composition)	Divide and conquer, holistic approach	When solving complex systems that exhibits mix architecture	Asan (2004)

9	**Concurrent Engineering**	Use of sequential model concurrently for different processes/stages that occur at the same time	Design and development of products and their processes overlap with planning of process development	Reduce lead time and overlapping activities, and reduce length of time in each activity	When experts from the multifunctional project teams are available to partake in design analysis	Yazdan*i et. al.*, (2014), Tomiyama *et al.*, (2009)
10	**Adaptable Design**	The capability of an existing design to be adapted to create a new or modified design based on the changed requirements	Allowing the adaptation of design giving thought to changes in requirements	To create designs that can easily be adapted for different and changing requirements	When design requirements are changed due to changes in customer requirements or advancement in technology	Tomiyama *et al.*, (2009)

Source: Author (Adapted from PDLDPJ (2019) Tomiyama et al., (2009) Szalvay et. al., (2004) Tomiyama et al., (2009) Creswell (2009) Adenowo et. al., (2013) Asan (2004) Yazdani et. al., (2014))

2.2.2 Typical design phases

Howard *et. al.*, (2008) analysed 23 engineering design process models to establish common trends amongst them. Design methodology begins with a design process model, which it is apparent from the table and supported by Tomiyama *et al.*, (2009), that it is made up of a logical sequence of phases in which tasks are completed. Howard *et. al.* identified the typical system design phases as listed and used in the table headings below. The typical design phases were mapped against the design methodologies identified in the previous section, to demonstrate their similarities or differences. Gericke *et. al.*, (2012a) also used the same approach to answer the research question: "What are the commonalities and what are the differences of design process models across disciplines?".

Table 3: The similarities between common system design methodologies

Design Methodology		**Establish the Need**	**Analysis of Task**	**Conceptual Design**	**Embodiment Design**	**Detailed Design**
1	ADDIE	✔	✔		✔	✔
2	DSM		✔	✔		✔
3	Agile Design	✔	✔		✔	✔
4	Design Centred		✔	✔	✔	✔
5	FMEA	✔	✔	✔	✔	✔
6	Top Down Design	✔	✔	✔		✔
7	Object-Oriented Design		✔	✔	✔	✔
8	Modular Design		✔		✔	✔
9	Concurrent Engineering		✔	✔	✔	✔
10	Adaptive Design		✔	✔	✔	✔

Source: Author (Adapted from PDLDPJ (2019) Tomiyama et al., (2009) Szalvay et. al., (2004) Tomiyama et al., (2009) Creswell (2009) Adenowo et. al., (2013) Asan (2004) Yazdani et. al., (2014))

Although some of the ten investigated design methodologies cover all typical design stages, it is in the detailing and emphasis of the phases where the methodologies differ. The below methods were eliminated for use in this study because of the given reasons:

- ADDIE and AGILE methodologies work best for smaller systems because of their sequential nature. TE: PDC business is involved in larger systems with lower volumes.
- DSM and FMEA require a thorough/detailed knowledge of the products by experts, thus unsuitable for TE: PDC as the products are relatively new and details unknown in most cases.
- Design Centred methodology leaves no room for change in requirements as the method is based on design e.g. CAD design

The *System Design Process* developed in this study and discussed in later chapters, integrating the characteristics of Modular design (i.e. dividing the system into manageable subsystems) and Concurrent Engineering (considerations about product lifecycle processes are integrated) to reduce design lead time and improve the quality of the product. The Adaptable design methodology allows the designer to reuse existing designs to meet the changes in the customer's requirements (Tomiyama *et al. (2009)*). TE: PDC could eventually (with experience and developed design knowledge and database) make use of the benefits of Adaptable design methodology, using a modular architecture.

2.2.3 System Development Lifecycle models

As mentioned previously, the *System Design Framework* and the *System Design Process* developed need to have a thorough lifecycle approach; which brings out the need to observe the system lifecycle variants and select the most suitable one. There are three types of lifecycle process models i.e. sequential, concurrent and unconstrained processes; and are discussed below (Adcock, (2017)).
The different system lifecycle development models that could potentially tie in with the discussed design methodologies are discussed below.

Waterfall Lifecycle model

Waterfall lifecycle process is a sequential lifecycle model that requires the completion of one phase before moving to the next, without going back to the previous one. Each stage relies on the input from the previous stage, the model that assumes that all requirements are known and properly defined (InnovativeArchitects (2020)).

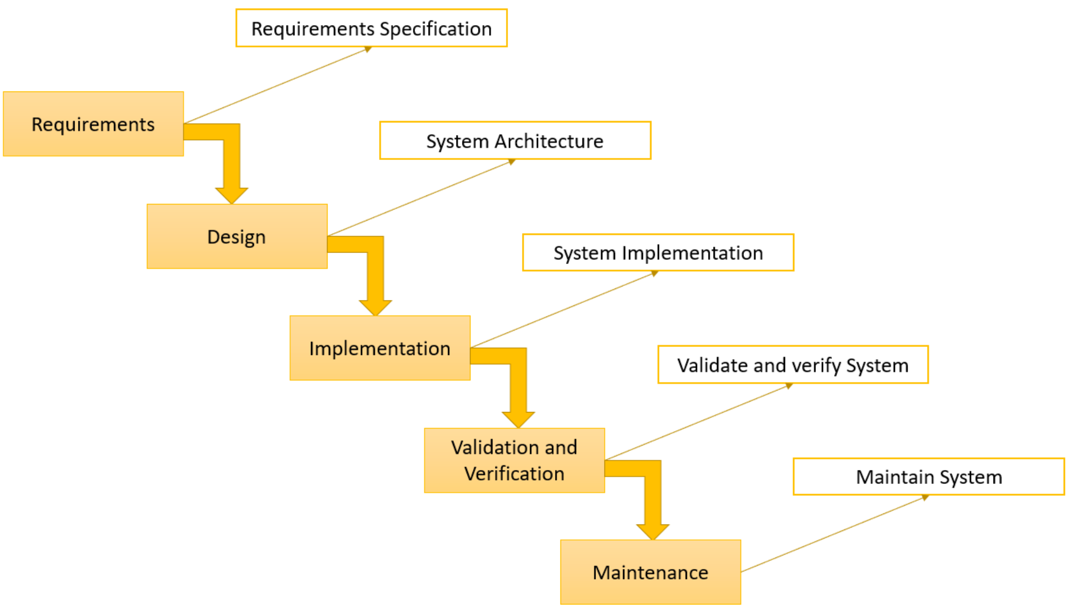

Figure 5:The waterfall lifecycle process
Source: Author (Adapted from ISO/IEC/IEEE15288 (2015))

Iterative Lifecycle model

Iterative lifecycle process involves an iteration of the waterfall model several times in small increments. It is primarily useful in cases where a system can be released in working versions or phases, where a set of requirements are implemented, tested and evaluated for each version (InnovativeArchitects (2020)).

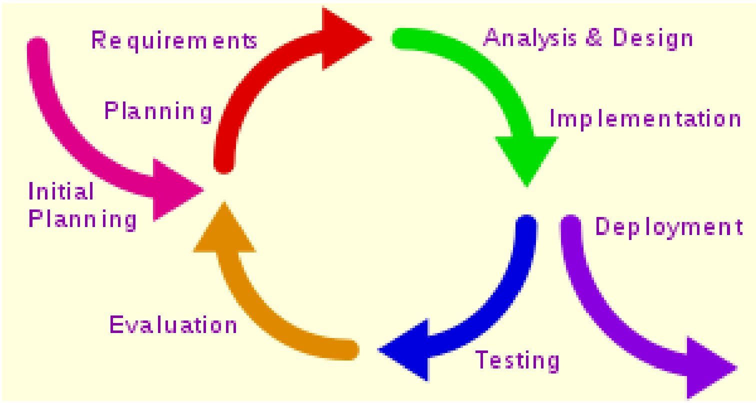

Figure 6: The Iterative SDLC process
Source: InnovativeArchitects (2020)

Vee-Model Lifecycle model

The Vee model in *Figure 7*, is best known as the Systems Engineering process model that emphasises on the management of decomposition and integration of the system to avoid rework. It also promotes the definition of the Verification and Validation plan and methods at the earlier stages of the project for preparation (Wynn *et. al.*, (2018)). The typical lifecycle states of the Vee model include exploratory research, concept, development, production, utilization, support and retirement phases.

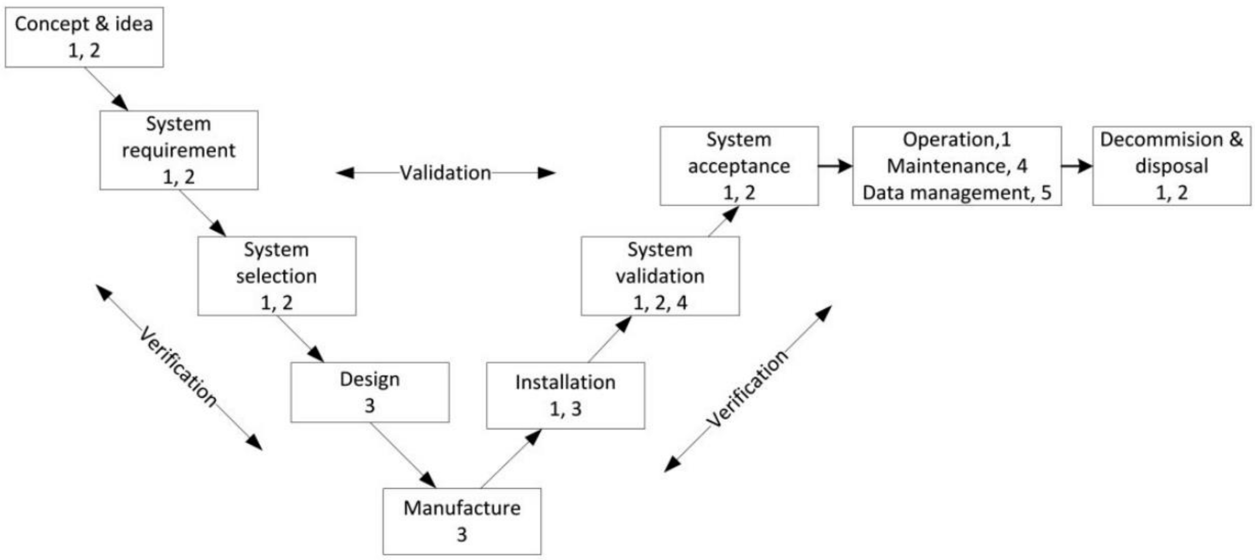

Figure 7: The Vee model for NPD process
Source: ((Asplund et. al., (2014))

RFS Loop Process model

RFS is an acronym for Requirement analysis, Functional analysis and allocation, and design Synthesis. The model has two loops which are iterative e.g. the requirements loop is an iterative process of revisiting the requirement analysis to trace each function performed back to a requirement. System analysis and control represents all activities that manage and control the RFS (Defence Acquisition University Press Fort Belvoir Virginia (2001)).

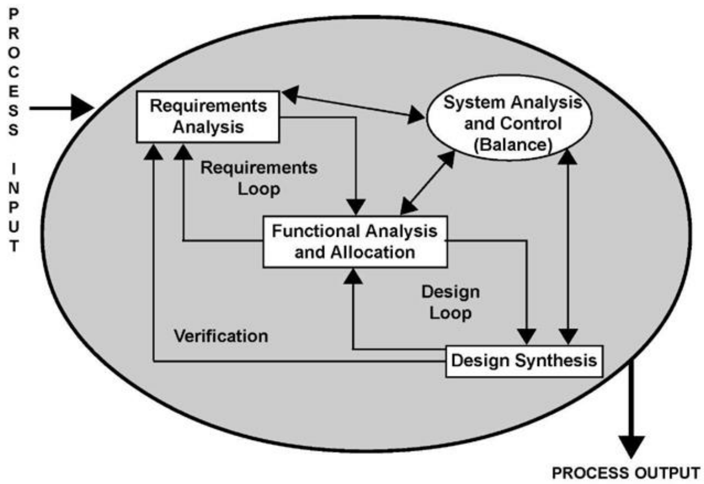

Figure 8: RFS loop
Source (Parent5 (2020))

Stage-Gate Process model

The stage-gate process model will ensure that every stage of the developmental model (From the Vee model) is sufficiently matured to proceed to the next stage of the system development. In this manner, costly loops can be avoided (Wynn *et. al*., (2018)). Below is the diagram showing the different stage gates involved.

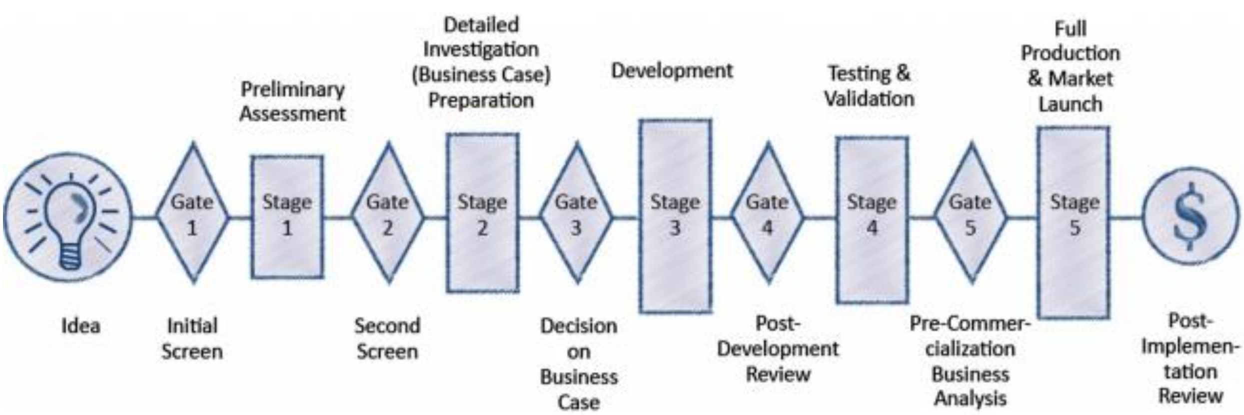

Figure 9: Stage gate process model for stage reviews
Source (Wynn et. al., (2018))

2.2.4 *Analysis of the System Development Lifecycle models and the System Design Methodologies*

Extensive research has been conducted on the comparison of different design methodologies. Gericke *et .al.,* (2012) conducted an analysis of existing design process models' comparisons in addition to other models, made of 124 design process models from nine disciplines. A different approach can be taken by comparing the listed System Design methodologies and CDLC models were made to observe any trend or similarities that may occur in terms of the process flow or structure. The table below shows the results my mapping the Systems Design methodology to the most likely SDCL of the five previously discussed model to match its behaviour.

Table 4: System Design methodologies vs. SDLC models

Design Methodology		**System Development LifeCycle model**
1	ADDIE	Interactive
2	DSM	Waterfall
3	Agile Design	Interactive
4	Design Centred	RFS loop
5	FMEA	Waterfall
6	Top Down Design	Waterfall
7	Object-Oriented Design	Waterfall
8	Modular Design	Waterfall
9	Concurrent Engineering	Interactive
10	Adaptive Design	Interactive

The above analysis indicates that that the Waterfall lifecycle model are more favoured, followed by Interactive lifecycle model.

In his research, Gericke *et .al.* found that most of the existing design models in literature handled product development as an isolated and monodisciplinary process. Below is a general critique of the models discussed in *section 2.2.3*. deduced from the from literature review as well as the observations from the above table.

The referred system lifecycle development models:

- Are meant for the development of products initiated by market pull,
- Considers either design or management issues, not both,
- Are linear,
- Trans-functional/transdisciplinary teamwork is not clearly represented,
- Lack of creativity,
- Consider problem and solution as separate entities (rather than co-evolving),

- Assumes that the problem is well defined.
- Do not explicitly consider post-design phases of the lifecycle in the predesign and design phase etc.

Similar trends can be observed when analysing the PDC Product Design and Development Process (PDDP). These threats are discussed later in the report.

One of the outcomes of this study is to provide a lifecycle design methodology which considers the design of a system/product based over the whole lifecycle, starting from the conception of an idea to the decomposition phase. Lifecycle design methodology takes into consideration not only the design phase but all other lifecycle phases that have an impact on the construction of the system.

This study seeks to build a system architecture that offers a bird-eyed view of a different perspective and attempts to address the above-mentioned design methodologies issues, by offering a solution that considers a different perspective as an alternative impulse for product design; and addresses through lifecycle design issues at the initial stages of the system lifecycle.

A combination of three design methodologies namely the Top-down design, Modular design and Concurrent engineering design methodologies has been used and tied in with the most suitable lifecycle development process, to represent a thorough lifecycle design methodology. The Vee-model is best suited for the application of this study because it addresses the basic set of Systems Engineering activities (Adcock (2017)). The post design phases of the Vee model correspond to the Design for X (DfX) characteristics (*section 2.4.1.2*), which was also used for the development of the *System Design Process* and brings a holistic lifecycle view.

2.3 System Success/Failure

Recent studies show new product success rates at launch of less than 60%; i.e. 54% for the UK, 59% for the US, 59% for Japan and 49% for Spain (Cengiz *et. al.*, (1998)). According to Blanchard (2008) the term *system* stems from the Greek *syst¯ema*, meaning an “organized whole.”
(Gomes *et. al.*, 2016) states that project success/failure definition can be linked to the inclusion of the triple constrains called the “iron triangle” or “triple constraints”, which are cost, time and quality criteria. However, this definition is insufficient as projects or systems are multidimensional and do not include only the project results but also the customer’s satisfaction as well as the satisfaction of other stakeholders.

2.3.1 System success/failure according to perspective

As stated by Puranam *et. al* (2015) performance of a major project is never a clear cut; its success or failure depending on whether it has delivered to cost and to quality in time, in-line with an individual’s expectations. Defining project success is an elusive topic (Soon Han *et al.* (2012)). Success is perceived in different ways by all stakeholder depending on their interests and priority (Madzibane (2018)). Perspective differences will explain the reasons why the same project could be deemed a success for one but a failure for another (Lim *et. al.,* (1999)). For these reasons, project success/failure will be defined from different viewpoints by considering the differing perspectives of people looking at the project.

Lim *et. al.*, (1999) proposed that success can be classified into two viewpoints, macro and micro viewpoints. Micro viewpoint is concerned with the completion criterion of the project per some predefined project goals (iron triangle included), while the macro viewpoint considers both the completion as well as the satisfaction, which can be measured through validation against stakeholder requirements. *System failure as used in this context is thus the failure of the creating system to deliver a created system which satisfies the macro viewpoint*.

There exists a set of factors which influence the success criteria. The below diagram in *Figure 10* summarises the two viewpoints:

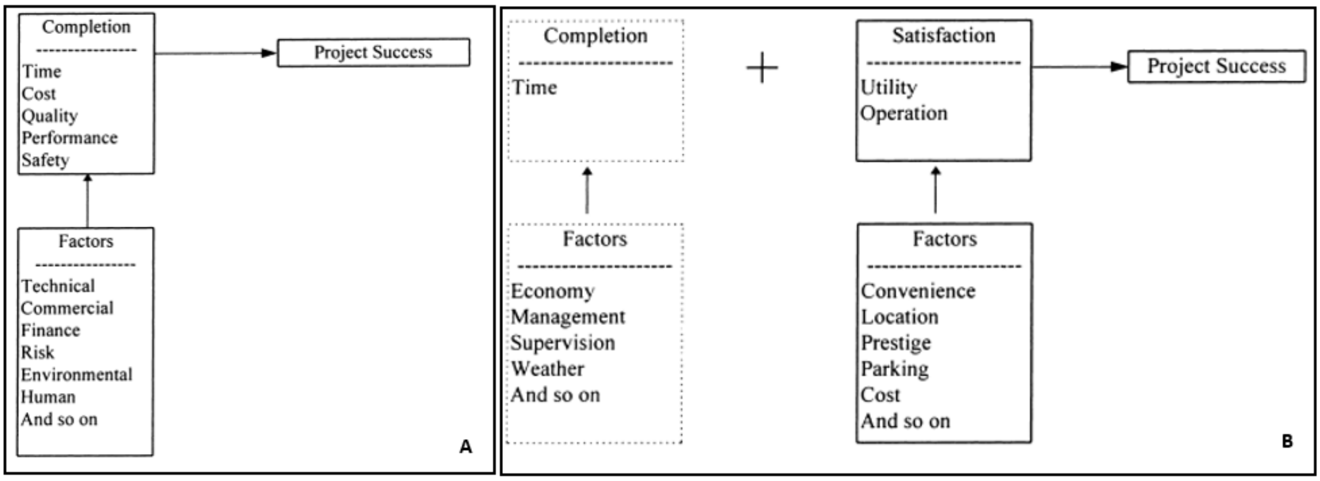

Figure 10: A: Micro viewpoint and B: Macro viewpoint to project success on a commercial building/property as an example Source (Lim et. al., (1999))

There is probably no "*absolute success*" in project management but simply "*perceived success*" (Gomes *et. al.*, (2016)). It is thus important for all stakeholders to be represented during the definition of project success (i.e. process of eliciting stakeholder requirements) to have a variety of success criteria and objectives defined.

On this basis thereof, success is looked at beyond the verification of the system. The satisfaction of stakeholders in this instance refers to the "System Validation" i.e. system's level test, which is planned for at the pre-design phase according to the developed *System Design Process*. This is due to the application of the Vee Model.

2.3.2 New Product Development design success criteria

New products are increasingly cited as a vital part of organisational success in the market (Cengiz *et. al.*, (1998)). It is thus important that a clear understanding of criteria that drive success in an organisation is obtained to leverage the resources dedicated to product development. Some researchers suggest that projects' success criteria should be specific to every project and should thus be determined at the beginning of each project (Gomes *et. al*, (2016)). The figure below shows the typical success criteria for NPD.

Figure 11: New Product Development success criteria (focusing on design)
Source: Author (Adapted from (Interbational_Design_Foundation (2019) and Cengiz et. al)

Criteria are a set of principles/standards by which judgement is made (Lim *et. al.*, (1999)). The success criteria from the above diagram can be explained as follow:

- Knowledge management: Organisations usually work in team silos. This makes knowledge sharing, which is important for system design, to be difficult. Organisational team knowledge structures need to be open, integrated and managed amongst the entire team.
- Stakeholder involvement: All stakeholders must be identified in the early stages of the project; they should be ranked according to their importance and stake in the project and be involved in decision making accordingly.
- NPD process and speed: Releasing new products to the market faster than your competitors gives the organisation an advantage. Although market-related factors are excluded speed has a direct link to the process. A new product must be released fast but with no compromise to the process of developing the product.
- Properly documented requirements and/or success criteria: This should be deployed at the early stages of the project and maintained throughout the system life, and communicated to stakeholders for a clear vision of the product/service.

- NPD strategies: Strategies can emerge as either a force from the competitiveness of the market (Defensive) or as a means of opening to the new market (Offensive); it is determined within the framework of an organisation through its objectives, resource availability, past and present performance etc.
- NPD teams: Teams must be multifunctional; integrated from different company departments to create a single team that shares a single vision.
- Technology: Technological innovation is central to NPD as it is concerned with the improvement of a product/service or development of new ones through technology.
- Top management support: Top management is responsible for decision making regarding the future of the company and projects to be undertaken. Management commitment to projects initiated generates enthusiasm in workers and provides a clear vision of the product/service.

A further analysis was performed by comparing the identified NPD success criteria with Total Quality Management (TQM) to support the definition of success criteria adopted by this study. According to David (2014), TQM has the following seven components summarised by the following diagram:

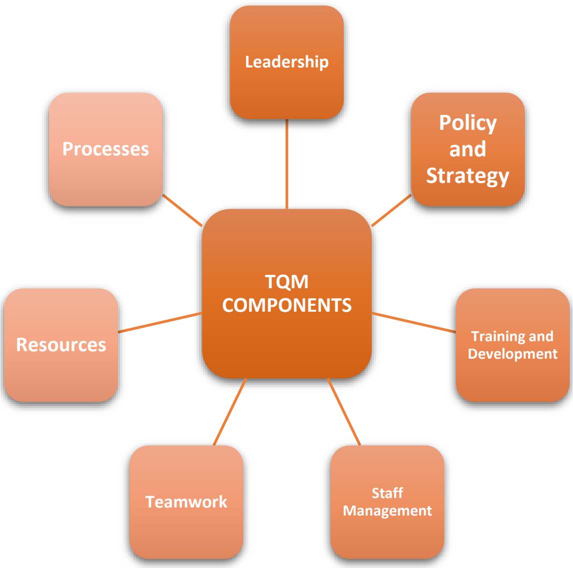

Figure 12: The seven components of TQM
Source: Author (Adapted from David (2014))

The above TQM components align with the NPD success criteria summarised by *Figure 11*; therefore, this will be the characteristics of success criteria as referred to in this study.

2.3.3 Typical design failure factors

Design deficiencies in products/systems, project overhauling, and delays are some of the main causes of system design failure. The cause and effect diagram (fishbone diagram) of *Figure 13*, summarises some of the possible factors of design failure by categorising the potential causes of a problem to identify the root cause.

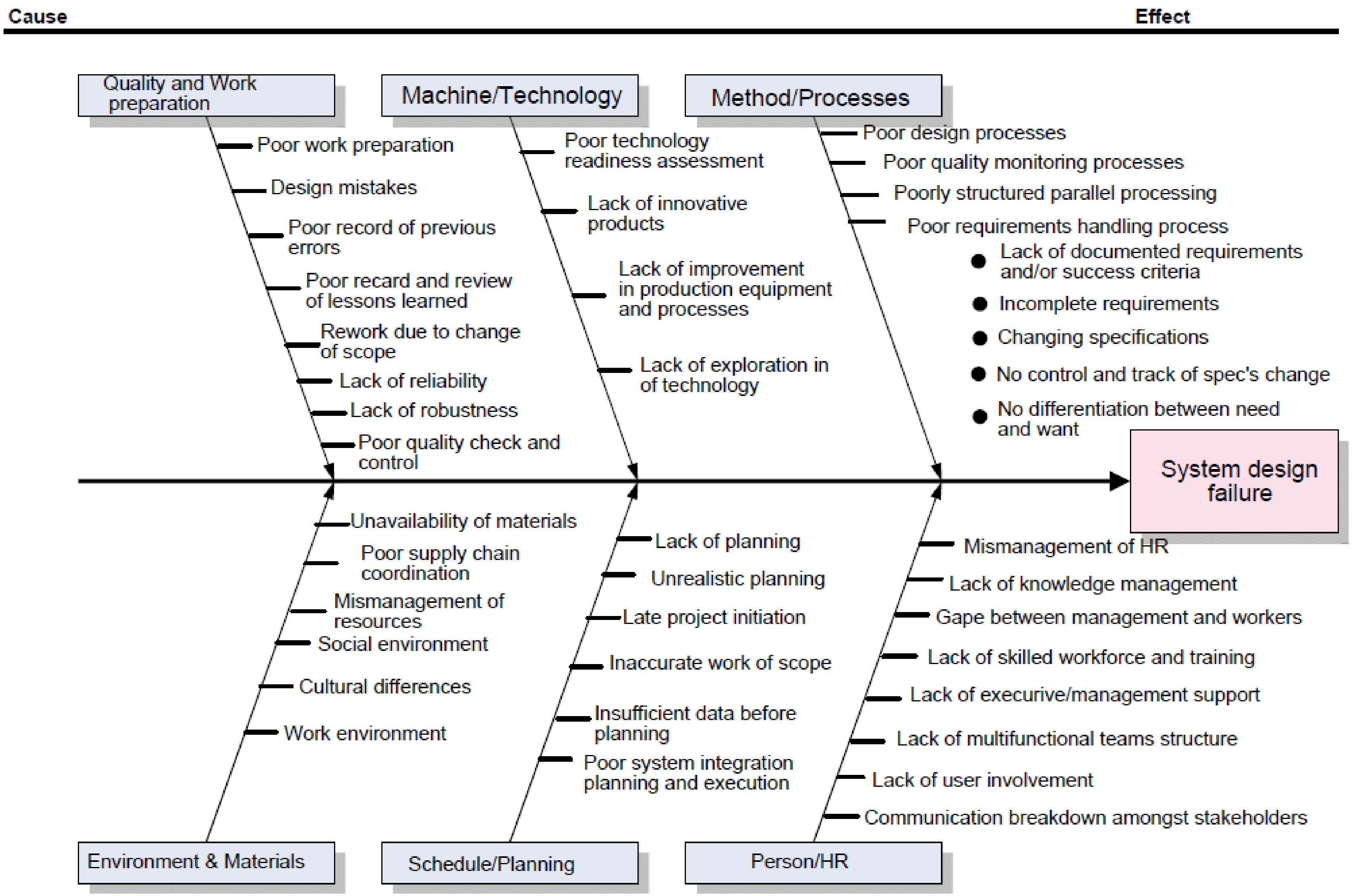

Figure 13: A representation of the system design failure factors using the Ishikawa diagram
Source: Author (Adapted from; Madzibane (2018), Standish Group (1995), Muhammad et. al. (2016), Cengiz et. al., (1998), Cooper (2019), Cooper et. al. (2010), Vertex 42 (2019)

Failure factors are a set of circumstances, facts or influences which contribute to a failed result (Lim *et. al.*, (1999)). The design failure factors were categorised into six categories according to their nature and represented using a Fishbone diagram (otherwise known as the Ishikawa diagram). The bones/body of the fish represents the causes of failure while the head is the effect of the causes of failure, hence the name: *cause-and-effect diagram*.

The study carried out by Madzibane (2018) identified communication breakdown among stakeholders, lack of documented requirements and/or success criteria as two of the top five reasons why project fail in Transnet. Madzibane developed a framework that can be used in Transnet. However, the framework does not address design matters and only focuses on megaprojects. From studying the diagram of *Figure 13* further, is visible that the identified failure factors are inversely related to the success criteria and quality management factors listed in the in *Figure 11* and *Figure 12* respectively. Thus, solidifying the argument of how success criteria should be defined.

The factors summarised in *Table 5* were deduced from *Figure 13*, to be the main cause of system design failure in OEM organizations. The design failure factors identified in the table are made up of both soft and hard systems. According to Gericke *et. al.*, (2012), most design methodologies focus usually on either the hard systems or the soft systems (i.e. design or management), rarely will the model focus on both aspects. The *System Design Process* should address both aspects. The failure factors were supported by different authors from five papers as shown in the table. The top five failure factors (According to their frequency of appearance in referenced reports) are highlighted in blue.

Table 5: Factors contributing to system design failure

	System Design Failure Factors	**Supporting Sources**				
		Montoya-weiss *et. al.*, (1994)	Cengiz *et. al.*, (1998)	Balachandra *et. al.*, (1997)	Ahmed *et. al.*, (2015)	Cooper *et. al.*, (2010)
1.	Lack of stakeholder involvement and management leading to communication breakdown	✓	✓	✓	✓	
2.	Lack of planning, scheduling and strategizing	✓	✓		✓	✓
3.	Lack of top management support	✓	✓		✓	✓
4.	Technology management/ Immature technology/ Poor Technology Readiness Level identification	✓	✓	✓	✓	✓
5.	Poor New Product Development processes	✓	✓	✓		✓
6.	Lack of requirements management including poorly defined requirements, incomplete specification documents and poor specification change management					✓
7.	New product development speed	✓	✓			
8.	Unclear scope and goals leading to scope creep.				✓	
9.	Rework due to change of scope and frequent design changes due to errors			✓	✓	
10.	Poor of material management			✓		
11.	Insufficient resources and resource allocation (unidentified roles and responsibilities)	✓			✓	✓
12.	Poor quality control processes (monitoring and tracking processes)				✓	
13.	Lack of technical and/or market knowledge and experience	✓			✓	✓
14.	Unrealistic time frames				✓	
15.	Poor Internal/External communication	✓		✓	✓	
16.	Interdependencies in cross-functional teams not identified resulting in poor integration process		✓			✓
17.	Having too many projects at a time / too large of a project					✓
18.	Inaccurate cost estimates/ Costs overrun	✓			✓	
19.	Proficiency in predevelopment activities (preliminary technical assessment, preliminary business/financial analysis, discussion of lessons learned from previous projects)	✓			✓	✓
20.	Hostile organizational environment / social environment			✓	✓	✓

2.4 Application of Systems Engineering

Systems Engineering is an *interdisciplinary process* that ensures that the *customers*' *needs* are satisfied throughout the system's entire *lifecycle* (Bahill *et. al*, (2009)). This definition was adopted for this study. Systems Engineering was chosen as an approach to solving the problem at hand because according to Bahill *et. al*, (2009) it is known to;

- Produce systems that satisfy the customer's needs, alluding to the concept of macro viewpoint for the definition of success,
- Reduce the total lifecycle cost of the system,
- Reduce the through lifecycle risk and
- Increase the probability of system success.

Hence this study focuses on the application of Systems Engineering to develop the *System Design Framework*. Customers include anyone who has the right to impose requirements on the system (Bahill *et. al*, (2009)). Hence the inclusion of the enterprise framework to consider the customer's view.

2.4.1 Systems Engineering competency framework

Systems Engineering Competency Framework is used to provide a common language with which to describe and discuss the competencies that are required by an organisation, an individual, a project and/or a training organisation, to conduct good Systems Engineering (INCOSE_UK (2015)). The set of competencies are said to be measurable and developed in consistent with ISO/IEC/IEEE15288 (2015), EIA632 (2004) and INCOSE Systems Engineering Body of Knowledge as defined by Adcock (2017). This paper adopts the definition of Systems Engineering and System Design as explained by the SE Competency framework and shown in *Figure 14*.

However, the *System Design Framework* would be incomplete without other Systems Engineering aspects which address a holistic approach to problem-solving. Therefore, other aspects of the Systems Engineering Competency framework have been incorporated to address other issues as identified previously and categorised as follows:

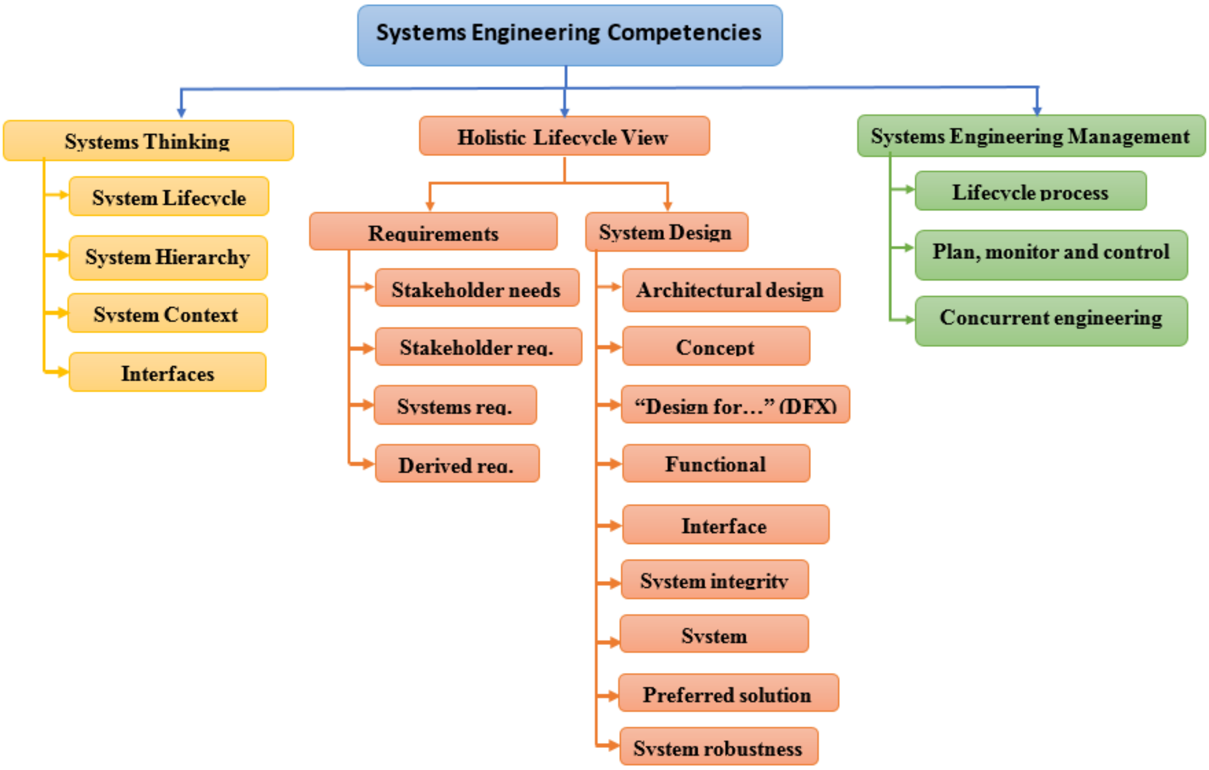

Figure 14: The Systems Engineering Competency Framework
Source Author (Adapted from INCOSE_UK (2015))

To make sure that the system concept is defined correctly, systems thinking is applied. Although the study is focused on the design phase of the system lifecycle, it takes a holistic lifecycle approach. It is inclusive of all system development phases from the earlier stages of identifying stakeholders, defining system needs to post-project phases till the disposal of the system (INCOSE (2015)). The study is cognisant of the effect of requirements definition, analysis and management (i.e. The Left-Hand-Side (LHS) of *Figure 2*). The study also takes into effects the Right-Hand-Side (RHS) of the system lifecycle process to system design for completeness; as well as the application of the Systems Engineering Management. This is represented in the *System Design Process* developed.

Systems thinking

Systems thinking was used to address all issues related to system context, hierarchy, interfaces and system lifecycle. Systems thinking originates back from 1956 by an MIT professor Jay Forrester when he realised the need to test new ideas about the social system the same way ideas in engineering are tested (Aronson, 1996). Systems thinking is a means of dealing with complex problems through holistic thinking, by placing a system into the context of a larger environment and studying the role and influence it plays in a larger whole. Its fundamentals lie in understanding the interdependencies of the systems i.e. how decisions and actions in one area affect the rest of the system ((Adcock (2017)), (Aronson (1996)), (Gharajedaghi (2006)), (Checkland (2000)) (INCOSE (2015)) and (INCOSE_UK (2015))).

To satisfy the macro viewpoint of system success (i.e. System completion and stakeholders satisfaction), both the hard systems methodologies (logical approach required to solve structured technical problems) and the soft systems methodologies (Disjoined incremental process required to solve fuzzy, ill-structured problems) have to be applied ((Checkland (2000) and (Lim et. a*l*., (1999)). Systems thinking is seen as a method of incorporating soft systems into hard systems, where the soft systems are people and process-centric issues as listed by *Figure 13*, as system design failures. Rees (2000) integrated soft and hard systems thinking and/or methodologies to develop a framework to be applied to solve challenges which resulted from long term financial strategy; while Mathiassen *et. al.*, (1989) combined the usefulness of soft systems thinking with the analytical dialectical thinking to show how the method would improve the traditional approaches to computer-based systems. The same approach was followed in this study.

Holistic lifecycle view

Lifecycle is characterised as "life to death" typically made up of the phases; while holism is the idea that "Whole is more than the collection of its part" ((INCOSE (2015)) and (Oxford Dictionary (2019))). To take into account the holistic lifecycle view, this study gravitates towards the INCOSE_UK (2015) definition of system design as it considers more than just the technical concerns. Also, the effect of all the system lifecycle processes of ISO/IEC/IEEE15288 (2015) i.e. agreement processes, organisational processes, project processes and technical processes, are taken into account by the *System Design Framework*. According to INCOSE (2015), the *System Design Process* can be divided into two parts, i.e. the problem/requirements definition process as well as the solution definition process, which are both represented in the typical design methodology phases discussed in chapters to follow. INCOSE_UK (2015) goes further by dividing holistic lifecycle view into two legs namely the requirements and system design (i.e. Problem domain and solution domain respectively)

Stakeholder requirements are used to define the problem to be solved ((Buede (2009)) and (INCOSE_UK (2015)). These requirements are elicited from the system stakeholder needs, which emerges from the stakeholders identified from throughout the system's lifecycle and categorised according to their power of influence to the project. Stakeholder requirements need to be complete, consistent, correct and attainable ((Buede, 2009)). *Figure 15* is the requirement quality matrix. It can be used to assist with the construction and evaluation of quality requirements during the requirement analysis process for already existing requirements .

Structural Element	Applicability	Score		Metric Name	Metric Value
Actor	1	0	Correctness	IQF1	0
Conditions of Action	1	0	Completeness	IQF2	0
Action	1	0	Consistency	IQF3	1
Refinement of Action	0	0	Clarity	IQF4	1
Object of Action	1	0	Non-ambiguity	IQF5	0
Refinement/Source of Object	1	0	Connectivity	IQF6	0
Refinement/Destination of Action	1	1	Singularity	IQF7	1
TOTAL	6	1	Testability	IQF8	0
Metric IRQ1	0.17		Modifiability	IQF9	1
Omission Ratio	5.00		Feasibility	IQF10	1

Figure 15: Construction requirement quality metrics to be used for quality requirements
Source (Halligan (1993))

To achieve the listed characteristics the following needs to happen:

- Elaborate on how the system will be used in detail,
- Understand the stakeholder objectives, and
- Define all the interaction between the systems, and
- Use the construction requirement quality metrics shown in the example below.

To promote the success of system design, it is important to manage the systems requirements (INCOSE_UK, 2015). This is achieved by ensuring that requirements are well documented and can be traced back to the original need, and thorough documentation handling and management. The following IDEF0 model shows the scenario (IDEF0 is explained in detail later in the chapter).

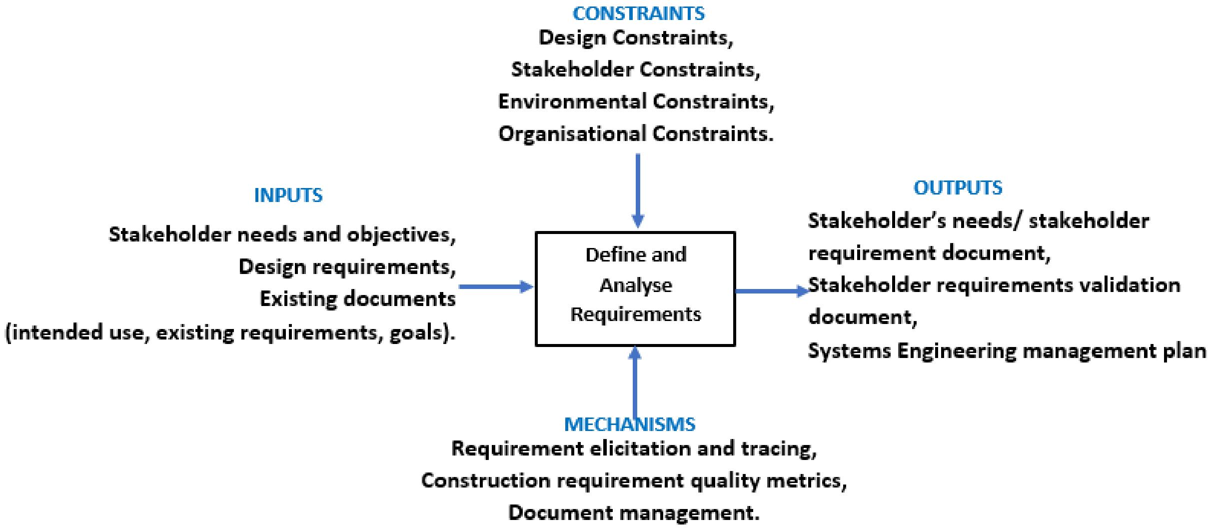

Figure 16: Requirement analysis model
Source: Author (Adapted from (Buede, (2009) and Parent5 (2020))

According to INCOSE_UK (2015), the requirements of a system describe the problem to be solved. Requirements thus have a direct impact on or feed into system design (ISO/IEC/IEEE15288 (2015)). The output documents for this phase will be used to derive a system design.

The second leg of the holistic lifecycle view is the system design and its parts can be summarised as follows:

Architectural design –To partition the system into system elements that consider all requirements.

Concept generation –To explore alternative solutions.

“Design for…” –To design for different attributes at the correct point in the lifecycle.

Functional analysis –To thoroughly understand what the system must do.

Interface management –To manage interactions across boundaries of a system or system elements.

System integrity –To maintain the overall coherence and cohesion of an evolving system.

System modelling & simulation –To represent the system entity or process to indicate performance.

Preferred solution selection – To select a solution that best satisfies the stakeholders’ needs.

System robustness –To indicate that a system can tolerate out of specification scenarios.

The Systems Engineering Competency framework as defined by INCOSE_UK (2015) and represented by *Figure 14* below, is used to define Systems Engineering Concepts and terminologies used in this study.

NPD requires an array of interrelated decision making in the early stages of design process, that requires the holistic perspective offered through Systems Engineering methods. The concept of Design for X (DfX) characteristics was brought in to ensure that the phases on the RHS of the V-model are included in the early stages of design by including the relevant requirements in the requirements definition stage ((INCOSE, 2015)). The table below shows some of the relevant DfX characteristics and their applicable system lifecycle phase.

Table 6: DFX characteristics and their applicable system lifecycle phases

DfX Characteristic	**System Lifecycle Phases: The RHS of the Model**							
	Manufacture/ Assembly	**Installation & System Verification**	**Acceptance & System Validation**	**User Satisfaction & Handover**	**Operation & Maintenance**	**Performance Monitoring**	**Modification and Retrofit**	**Decommissioning & Disposal**
Manufacture and Assembly	✔	✔			✔		✔	
Quality	✔	✔	✔	✔	✔	✔	✔	✔
Reliability	✔	✔	✔	✔	✔	✔		
Availability	✔	✔	✔	✔	✔	✔		
Maintainability	✔			✔	✔		✔	
Safety	✔	✔	✔	✔	✔	✔	✔	✔
Performance	✔		✔	✔		✔		
Human factor (Operability)	✔	✔	✔	✔	✔	✔	✔	✔
Environment	✔			✔			✔	✔

***Source: Author (Adapte**d from EN50126-1 (1999) and Caruso et al. (2010))*

The *System Design Framework* will consider all these, but also taking the effect of soft systems involved. The use of DfX will help address the post-design phase lifecycle failure factors (e.g. Quality, Persons/HR, environment etc.) listed in *Figure 13,* by planning for post-design phase activities earlier in the lifecycle.

To close off the loop, and show the importance of holistic lifecycle view, a study was conducted on the influence of holistic lifecycle view competencies (represented as contributing factors to design challenges in the below table) on success or failure of design projects of OEM type organisations in the transport sector. *Table 7* maps these projects with some of the SE Competencies to indicate the reasons for projects failure for each of the projects, as related to the competencies.

Table 7: Past design projects and their reasons for failure/challenges

Contributing Factors to Design Challenges/Failure	Afro 4000 PRASA	London Underground Limited	California HST	Angrois HST crash	Jubilee & Northern line upgrade	Boeing 737-max 8	Ford Pinto	CityLink Melbourne Control System
Stakeholder management/ID	✓	✓			✓			
Requirements management	✓	✓	✓	✓	✓	✓	✓	✓
Planning, monitoring and control	✓	✓	✓	✓	✓	✓	✓	✓
Standards	✓	✓		✓			✓	
Architectural design	✓	✓		✓	✓	✓	✓	✓
Interface management				✓	✓	✓	✓	✓
System integrity	✓		✓	✓			✓	
System robustness		✓		✓		✓		
Human factor	✓	✓			✓		✓	
Quality	✓	✓	✓	✓		✓	✓	

Source: Author (Adapted from Handgraaf (2013), HealthSafetyExecutives (2006), Smith & Shirley (1987), Forsberg & V'zquez (2016), INCOSE Transportation Working Group (2016), Slater (2019), Ford (1978))

According to the findings, requirement management had an impact on failure for all the identified projects; thus, indicating the importance of properly defining and maintaining the requirements. According to Standish Group (1995), 42.3% of project failure failures were related to requirements. In the research conducted by Madzibane (2018), lack of documented requirements was identified as one of the major causes of project failure in Transnet. Thus, although the study is focused on the design phase, requirements management cannot be ignored.

This paragraph discusses the reason for design failure in some of the products mentioned in the table above. The derailment of the LUL was due to detachment of the traction motors. The design characteristics of the rolling stock were not compatible with the speed at which the train was running at, leading to excess vibrations on the motors, and ultimately the failure of the LUL (HealthSafetyExecutives (2006)). The next example is of Ford Pinto vehicle's failure. In the pre-launch test, Ford realised that the rear end collisions propelled the gas tank onto the rear axle causing the tank to rupture and catch fire on their mountings because the system was not robust enough to withstand the environmental stress. Thus, interfaces were not managed properly leading to a compromise in system integrity and failing to meet the requirements (Ford (1978)). As reported by Handgraaf (2013), PRASA did not follow the RSR processes for Lifecycle Phases as outlined in SANS 3000, resulting in design irregularities. The investigation revealed that AFRO 4000 fleet exceeded the vehicle gauge height on South African networks (Handgraaf (2013)).

It is observed from *Table 7* that the contributing factors to design failure of past NPD projects concur with those represented by *Figure 13*; thus, validating its relevance.

Systems Engineering Management

Systems Engineering Management or SEM knowledge area is concerned with the management of resources and assests allocated to perform systems engineering, often in the context of a project or a service. SEM is distinguished from Project Management (PM) through its focus on the technical or engineering aspects project (Adcock (2017)). To further distinguish between SEM and PM, two domains i.e. system domain and project domain, are differentiated.

A system is any process that converts inputs into outputs; it is composed of subsystems arranged together to achieve a common goal. On the other hand, a project is a formal enterprise that addresses the processes of designing and developing systems (Eisner (2002)). Projects only deal with a certain defined portion of the system lifecycle e.g. design phase, thus having a limited scope while a system will exist to its disposal (Eisner (2002)).

Over the years there have been studies conducted to investigate the importance of integrating Systems Engineering and Project Management. Design as part of the Systems Engineering process is an iterative and dynamic process (Wessels *et. al.*, (2012)). However, the systems engineering process is "static" because of its absence of time constraints and/or management of resources in its processes e.g. The Vee-model does not specify time and resources needed. To bring a system into being, Systems Engineering and Project Management must be integrated to provide the management of schedule as well as the consumption of resources. (Wessels *et al.* (2012))

In 2011 and 2012, INCOSE and (Project Management International) PMI recognised the importance of integrating Systems Engineering and Project Management to improve the organizational Return on Investment and reduce risk, they conducted a survey, whose results highlighted the importance of integrating Systems Engineering and Project Management to lessen the presence of unproductive tension between the two professional bodies (Conforto *et. al.*, (2013)). Baron *et al.*, (2015) argues that organizations' competitiveness can be improved through finding a balance between system development and project management, to achieve performance and success in New Product Development (NPD). Baron *et al.* developed the DECWAYS method and tool through the comparison and analysis of standards from both systems engineering and project management domains and align processes from these standards. Baron *et al.* aligned the standard ISO/IEC 15288 with the Project Management Body of Knowledge (PMBoK) from Project Management. Thus, DECWAYS should facilitate project management by providing means of formalising decision making, traceability, and project visibility (Baron *et al.*, 2015). In the study by Sharon *et. al*, (2011), System Engineering Management (SEM) is presented to be the integration between SE and PM.

In this study, the Systems Engineering Management approach will be considered as an option for integrating the two. Although PM is intensely applied within TE, the intersection between SE and PM currently does not exist within TE: PDC. The current NPD process does not indicate the association of system design activities with project management processes.

Systems Engineering Management or SEM can be achieved through the integration of three major activities namely; development phasing, systems engineering processes and lifecycle integration (Defence Acquisition University Press Fort Belvoir Virginia (2001)). The interaction of the activities is summarised by the diagram below and explained in the paragraph that follows.

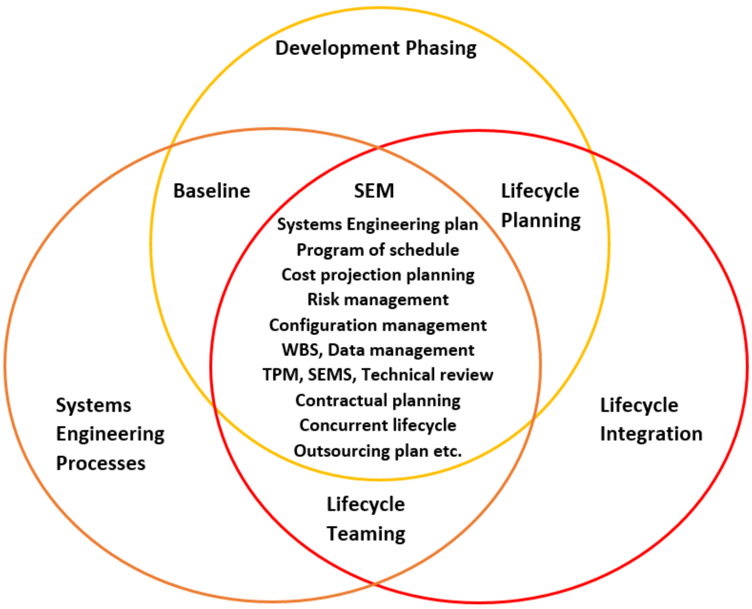

Figure 17: The System Engineering Management
Source: Author (Adapted from Defence Acquisition University Press Fort Belvoir Virginia (2001))

The development phasing controls the design process and makes use of the three developed baselines i.e. conceptual, system and subsystem (which can go an abstraction lower to detailed subsystem), that coordinates design efforts and govern each level of development.

The systems engineering process has the following stages, requirements analysis, functional analysis and allocation, as well as the design synthesis stage (i.e. RFS), balanced by techniques and tools collectively called systems analysis and controls (e.g. Risk management, configuration management documents, data management, technical reviews and audits, modelling and simulation etc.). It is a problem-solving process that is recursive through all developmental stages and used to transform the needs and requirements into a set of product and process descriptions and develop information for decision-makers.

The lifecycle integration is achieved through the concurrent consideration of all system lifecycle needs during the development process. This activity includes the product and process developmental planning as well as the integration of the multiple functional concerns into the design and engineering process (Defence Acquisition University Press Fort Belvoir Virginia (2001)).

An important element that arises from these activities is the Systems Engineering Management Plan (SEMP). SEMP constitutes the overall planning including the necessary directives and guidance material for the successful implementation of requirements and the identification, analysis and control of risks ((Blanchard *et. al.* (2007)0 and (INCOSE_UK (2015))). It is used to indicate how the multifunctional teams will be organised, tasked and trained to achieve the requirements (Defence Acquisition University Press Fort Belvoir Virginia (2001)). The output of the SEMP includes amongst others, the Work Breakdown Structure (WBS) which is a foundation for the system analysis and control activities, cost projection, customer, producer, supplier activities etc.

The SE Competency framework takes the definition of System Engineering Management further by considering management of concurrent lifecycle activities and the parallel development of system elements and management activities through concurrent engineering. Concurrent engineering enables lifecycle activities and/or elements that can occur concurrently to be executed simultaneously using multi-disciplinary teams in design. SEM will be part of the *System Design Framework* by considering the thorough lifecycle integration, system design management plan, concurrent design, early-stage planning, monitoring and controlling amongst other factors. As one of the recommendations which came out of this study, the author will propose that these planning elements be addressed in a SEMP for each TE: PDC development project.

2.4.2 Systems Engineering frameworks

Grant *et. al.*, (2014) define frameworks as “blueprints” used to clarify the structure and vision of a system. The *System Design Framework* was expanded into the Systems Engineering Design model which has a holistic view by considering all phases of the system lifecycle process. It draws inspiration from the concepts of the architectural framework. In this study, a *System Design Framework* was developed. Over and above that, a *System Design Process* was deduced from the framework to indicate how the framework can be applied. This section summarises the framework, models and processes considered for the development of the framework and design model.

To reconcile the different stakeholder views, a systems approach was used taking an enterprise perspective. An enterprise is defined as one or more organisations sharing a defined mission, goals and objectives to offer an output of either a product or service (Adcock (2017)). It consists of a network of interdependent resources including people, processes, organisations, technologies, and funding. The enterprise frameworks used is the Zachman framework, to help understand the customer’s needs and viewpoint.

The Zachman framework

The Zachman Framework provides means of viewing an enterprise and its information systems from different perspectives, also showing how the components of the enterprise are related to each other (Singer (2007)). It is a fundamental structure for Enterprise Architecture and provides a proactive business tool, which can be used to model an organisation’s existing functions, elements and processes, and help manage business change (Zachman (2007)). The Zachman framework is represented as a 6x6 matrix grid showing the different perspectives as below.

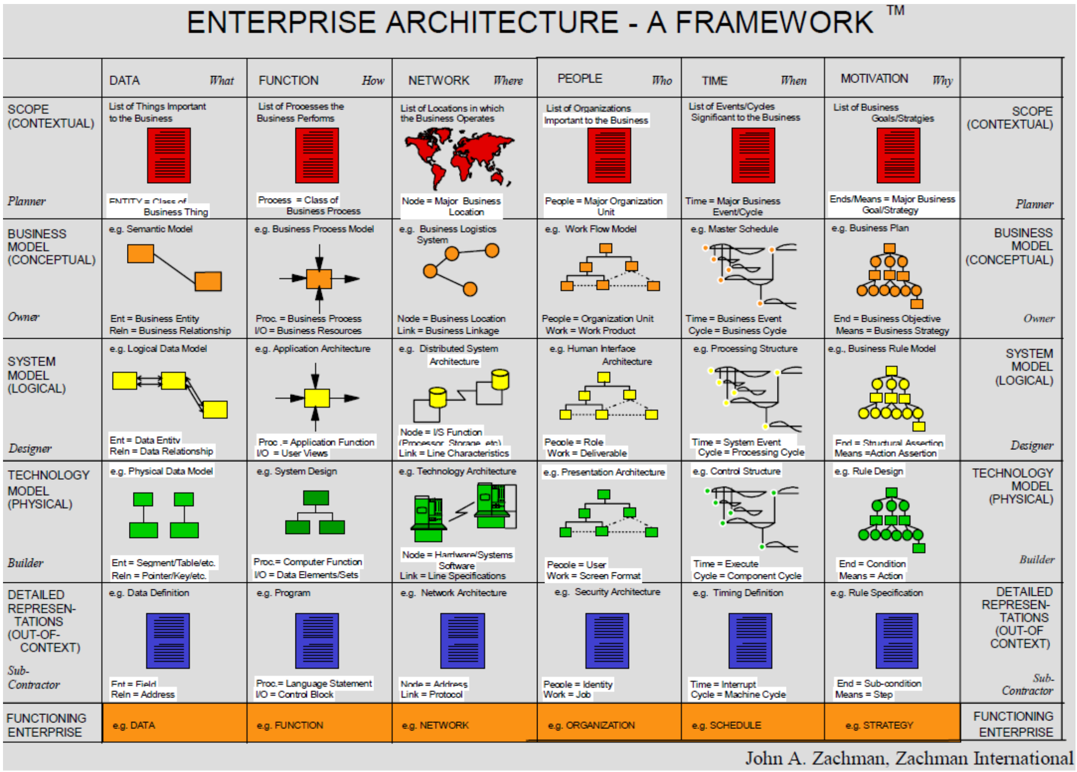

Figure 18: The Zachman framework
Source: (Zachman (2003))

There exists an overlap between the Zachman framework (i.e. headings row) and the CONcept of OPerationS or CONOPS. The Zachman framework captures from different viewpoints (i.e. contextual, conceptual, logical and physical), the information regarding the data, function, network, time, people and motivation which the system uses through its lifecycle as depicted by the diagram of *Figure 18*. To mimic these characteristics of the Zachman framework, CATWOE and RFS loop will be used in the *System Design Framework* developed. They are explained below.

CATWOE Mnemonic

The CATWOE analysis (Adapted to COAWTET to depict the questions addressed by the CONOPS document i.e. Who, How, What, Where and When), is performed to develop the root definition by defining the necessary elements that constitute a human activity system from a different perspective and defined as follows according to Mirijamdotter *et. at.*, (2014):

Table 8: CONOPS definition

Element	**CONOPS Question**	**Definition**
Customers	Who	Beneficiaries of the system or those who might be victimised by the system (e.g. Clients)
Owners	Who	The people/ person of a certain organisation who has the ultimate say over the project
Actors	Who	The person (s)/institution who/which will be performing the required transformation/ functions
World-view	What and Why	How the world views the System of Interest (SoI)
Transformation	How	The purposeful processes that will transform the system inputs to output
Environment	Where	Constraints acting on the system/situation
Time	When	The period of occurrence of events

Source: (Mirijamdotter et. at., (2014))

Learning from the presented enterprise architectures, multiple viewpoints can be managed and projects success/failure can be defined using these perspectives. CATWOE analyses will be integrated on the Zachman framework to help identify stakeholders and find a way of addressing project failure factors by defining the problem correctly in using CONOPS.

The concepts represented here on forth were used for the development of the *System Design Process* model. Drawing from an organising framework developed by Wynn *et. al*., (2018), which positions and maps the different Design and Development Process (DDP) models to one another, the *System Design Process* model will be developed to guide the process of new product development. Bahrami *et. al.,* (1993) recommends the use of a pluralistic approach, where design processes are simultaneously perceived from different viewpoints, and that is the approach taken. The below diagram is the organising framework; the macro-level procedural models are more suitable for the application at PDC.

Figure 19: The organisation framework for DDP models
Source: Author (Adapted from Wynn et. al., (2018))

Macro-level, not to be confused with macro viewpoint defined earlier, suggests that the model focus is on the projects structure and/or design process in context, and models in the *Procedural* type category convey recommendation of best practice according to Wynn *et. al*. The concepts of three of the Macro-level procedural models namely, the Vee model, the stage-gate process model and the concurrent engineering model will be interacted to produce the *System Design Process* model. This is because:

- Given the complexity of the projects undertaken at PDC, no single model can address all issues. Research suggests that most situations can better be defined and solved by more than one model (Wynn *et. al.,* (2018)*)*.
- Large scale, complex engineering projects (like that of PDC) will require many tasks, leading to a densely populated web of information flow and interdependencies. The application of the Vee model with concurrent engineering will divide the problem into subsystems and solve them concurrently, saving time.

The *System Design Process* was completed from a combination of the RFS loop process, the IDEF0, as well as the three macro-level processes discussed above. Two of the three models to be used have been discussed in previous sections. The next section discusses the IDEF0, that is the only missing model which was not defined.

IDEF0

The *System Design Process* model was represented in the form of an IDEF0 model. IDEF0, which is an acronym that stands for Integrated Definition for Function Modelling, originates in the 1970's from the United States Air Force's Integrated Computer-Aided Manufacturing (ICAM) program. It is a process model that addresses how inputs are transformed to outputs through some function, activity or task, representing an interaction between the functional and physical components of a system (Buede, 2009). IDEF0 comprises of functions (represented by a box and can be a noun or verb phrase) and flow of material, the energy of information (represented by an arrow labelled by a noun phrase) as depicted in *Figure 20* below. The flows are Inputs, Constraints, Outputs and Mechanisms (ICOM's).

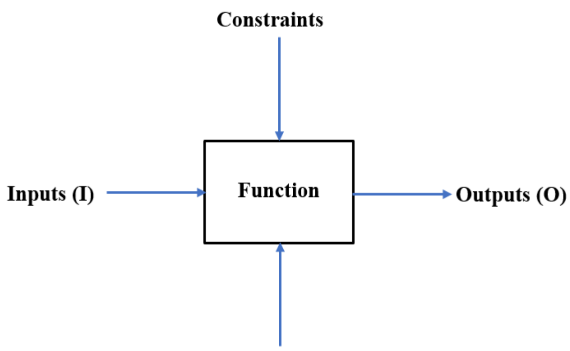

Figure 20: IDEF0 diagram
Source: Author (Buede (2009))

IDEF0's purpose is to answer definitive questions regarding transformation, establish system boundaries and establish a single viewpoint with the perspective from which the system is observed. IDEF0 will be used to represent the *System Design Process* for TE: PDC by connecting the outputs of the previous IDEF0 stage to be inputs and/or constraints of the next IDEF0 as seen in *Figure 21* below.

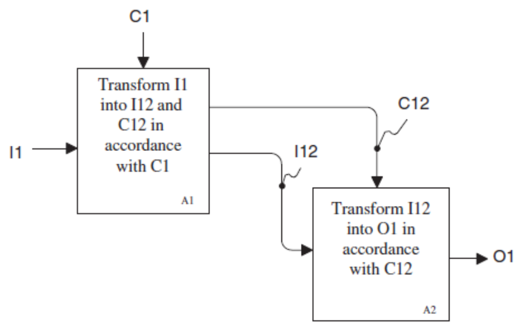

Figure 21: Combining two IDEF0 models
Source: (Buede (2009))

The iterative nature of the RFS loop will be applied at different levels (i.e. system, subsystem and component) to enable the revision of design at each level. This was combined with the review of design at each Stage-Gate to enforce accountability and progress within the project. This is further discussed in Chapter 4 of this document.

CHAPTER 3

3 RESEARCH METHODOLOGY

The technique used to identify, determine and process the information applied to conduct the study leading to the development of the *System Design Framework* and the *System Design Process* is discussed in this section. The research onion of Saunders *et. al.* (2007) was used as guidance to identify the research process to be followed in this study, its components are discussed in detail in this section as used in the research.

For better understanding, the problem was conceptualised from the critical literature review, analysis of archival data and further verified through interviews to solidify the argument that: The *System Design Process* has an impact on the success/failure of projects in TE PDC as an OEM, and determine the possible factors which may lead to project failure. This brings forth the concept of triangulation, to increase the confidence in findings through the use of two or more independent measures (Heale *et. al.,* (2013)). The developed framework and model were evaluated through the focus group discussion.

3.1 Research Design

Learning from the Innovation Design Engineering Organisation or IDEO design thinking, the below procedural plan was developed and executed for the collection, measurement and analysis of data to answer the research question effectively.

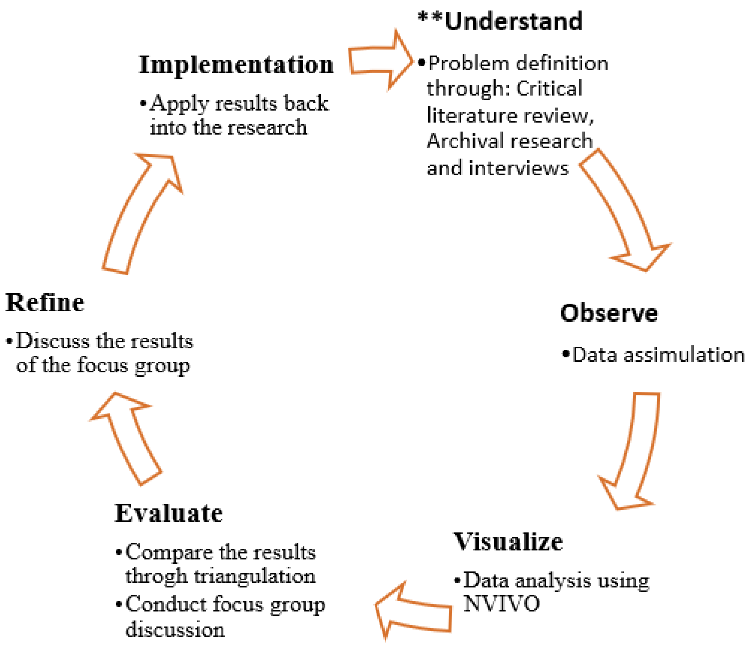

*Figure 22: The research design used for the study (**start)*
Source: Author (Adapted from (IDEO, 2020))

The IDEO design process helped create a strategy for the design process for the study. The first step was to understand the problem through critical literature reviews. Twenty design failure factors were deduced from there. These failures were interrogated through the analysis of archived company data as well as interviews. Results were visually represented using NVIVO and evaluated through the focus group session.

3.2 Research Framework

This section describes the strategy that will be applied to implement the research design. The research philosophy to be adopted by this study is Positivism, taking a deductive approach. The research onion of Saunders *et. al.,* (2007) is peeled from the outside going in, to expand on each circled topic.

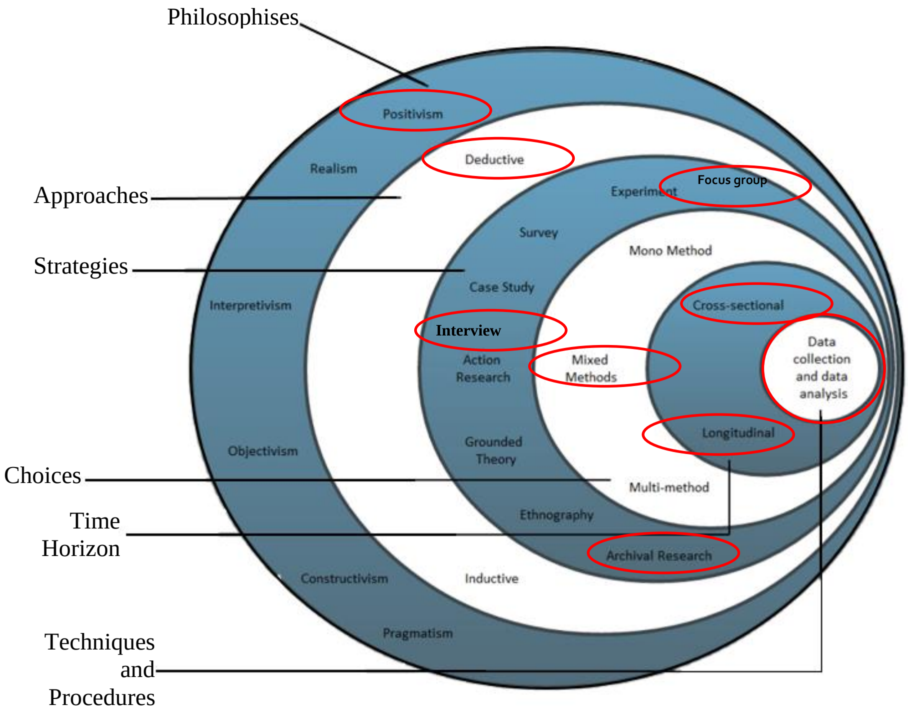

Figure 23: The research onion
Source: Author (adapted from Saunders et. al., (2009))

3.2.1 Research philosophy: Positivism

Positivism refers to the scientific study of the social world (Turner (2001)). It is the basis of a paradigm, whereby it is believed in the philosophy in which causes determine effects or outcomes Creswell (2009)). Turner (2001) states that the objective of this type of philosophy is to formulate abstract and universal law on the operative dynamics of the universe. In this research, a framework and model are formulated to be applied in a system to potentially eliminate failure.

According to Williamson (2018) positivist researchers often deduce hypothesis from literature for testing in their studies, the same concept was applied in this study.

3.2.2 Research approach: Deductive

The choice of which research strategy to apply was determined by how clearly an applied theory is already available at the initial stages of research (Henderson (2016)). A deductive approach was selected. This was because the concept of system design failure has been extensively investigated in the past. In the deductive approach strategy, the already available theory is verified on its casual relationships of variables, where a hypothesis needs to be validated (Henderson (2016)).

Deductive style of reasoning is broadly associated with positivist research approach as it is linked to hypothesis testing (Williamson (2018)). With deductive reasoning approach, an argument moves from general principles to particular instances. In consequence, this study investigates broad reasons to why design projects fail and narrow them down to reasons applying specifically to TE: PDC.

3.2.3 Research strategy, choice, technique and procedures: Concurrent triangulation

As part of ensuring the validity and reliability of data, concurrent triangulation method was used. Triangulation Data was collected through multiple sources including literature review, archival research, interviews and focus group making the research choice to be a mixed-method choice. The below concurrent design visual model shows the initially proposed research strategy.

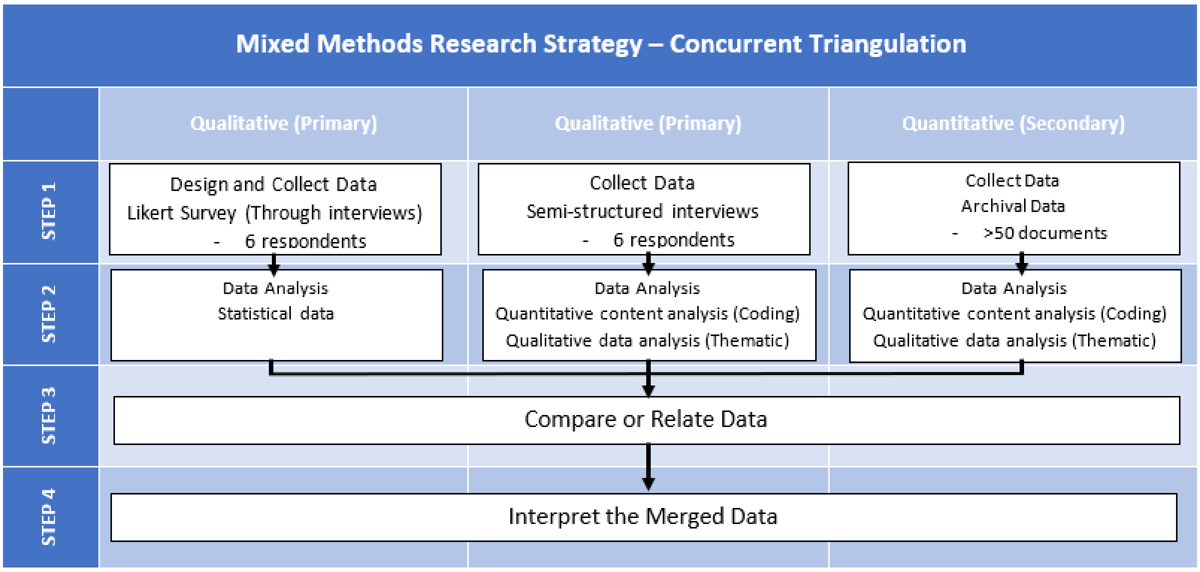

Figure 24: Initially proposed research strategy Source:
Author (Adapted from Creswell (2009), Marshall et. al., (2013) and Madzibane (2018))

The research strategy was deemed sufficient for 50/50 research. However, due to insufficient data collected (i.e. 50% interview participant response), it was important to enhance the method by including focus group discussion, which would be used as a means of validating data. This is further explained in the sections that follow. The diagram below shows the complete research strategy used for this study, inclusive of the Focus Group.

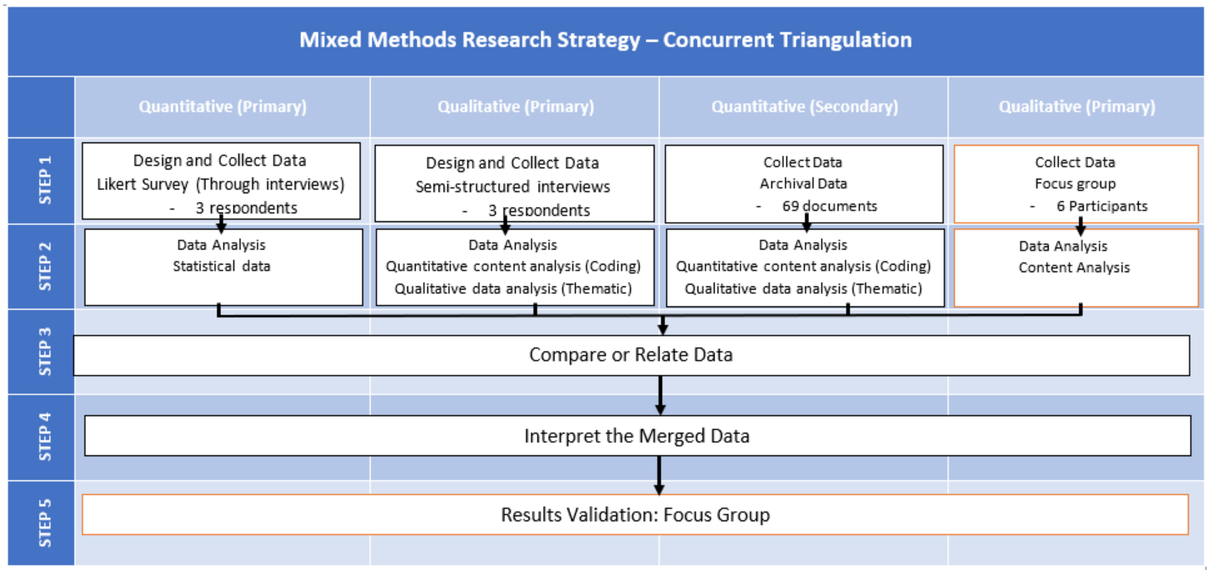

Figure 25: Design visual model showing the concurrent triangulation method applied in the study
Source: Author (Adapted form Creswell (2009), Marshall et. al., (2013)and Madzibane (2018))

It was important to introduce a focus group (i.e. step 4) to evaluate the results obtained from data analysis and the effectiveness of the framework and process developed. Concurrent data collection method requires a shorter time as compared to sequential methods. The use of concurrent strategy required expertise and effort from the researcher. It was thus important to ensure availability of experts.

Archival Research

Archival research was used to determine the different design and development methods used in Transnet, their evolution and effect on the success or failure of previous projects carried out. This was accomplished by interrogating and comparing the two methods used i.e. The Product Development Process used by TE: PDC and the Project Lifecycle Process used by Transnet Group Capital. Archival data was chosen because of the availability of data (administrative records and documents) from TE: PDC database, also from one of the projects carried out by TE: PDC as it was recently completed. The data collected was secondary because it was not compiled by the researcher.

In this study, archival research was applied over both longitudinal and cross-sectional time horizon. This is because, although data from one project was used, documented processes and templates that were analysed were over a long period (i.e. From the conception of PDC).

Interviews

Semi-structured interviews were carried out to discover the respondents' viewpoints regarding the situation relevant to the broader research problem and promote open conversation to uncover points which may have been looked over by the researcher (Davis (2017)). The failure factors enlisted from the literature review and rated by the participants of the interview on a Likert scale are summarised in Appendix A. More failure factors that were relevant to PDC were uncovered during the interviews. These were also rated together with the other factors to narrow them down to most affecting factors.

A convenience sampling method was used, where all individuals meeting the demographics described in the below table were invited. It was ensured that all participants of the interview were currently working for or have previously worked for TE: PDC (which is the system of interest). The following table summarises their profile.

Table 9: Interviews sampling profile

Interviews	
1. Age group	30 - 60
2. Minimum number of years of experience in PDC	5
3. Number of projects executed at PDC	At least 2
4. Systems Engineering knowledge	Must have at least practised/applied Systems Engineering in their line of work

Source: Author

The purpose of the interviews was to:

- Validate the previously identified failure factors from the literature review
- Validate the *System Design Framework* and *Process*.

It was uncovered that the validity of the viewpoint from the respondents was compromised because of the sampling profile requirement not fulfilled. The above objectives were not met as none of the participants were knowledgeable in Systems Engineering thus, unable to evaluate the framework. A minimum of six participants was expected for interviews but only three responded were interviewed, making the response rate achieved 50%. Also, the viewpoint of the participant was narrow (i.e. only from an operational point of view) as the participants were from the same level of employment (i.e. only designers). Adding variety (e.g. managers) would have broadened the viewpoint and expanded more on the failure factors. This brought the need to further expand the research methodology and introduce other ways of validating data, by bringing in a panel of experts in Systems Engineering through a Focus Group discussion.

Focus Group

To close the loop and answer the second research sub-question (stated in *section 1.5*) and meet the third research objective (stated in *section 1.6*), a focus group was conducted. Focus group, otherwise known as group discussions, involve a group of people usually between 4 and 10, brought together to discuss the research topic (Ritchie *et. al.*, (2003)). This sample size is supported by Saunders *et. al.*, (2007), where the author determined that a group of four to twelve participant is sufficient, depending on the nature of participants and the topic matter. Similar to in-depth interviews, focus group interviews are also a type of exploratory study (Saunders *et. al.*, (2007)). Saunders further explains that focus groups may be used as a means of validating data, such as results of the questionnaire that had been analysed, just as it has been utilised in this study.

Ritchie *et. al.* suggests that focus groups be used after in-depth interviews to discuss issues at a more strategic level; as well as to discuss the underlying issues and possible solutions. In this study, a focus group made of subject matter experts was conducted after in-depth interviews, to analyse the developed *System Design Framework* and *Process* and to determine whether or not the framework and process would be able to tackle the already identified failure factors. It was also used to determine whether the research methodology used is sufficient for the type of study conducted.

For the focus group, six participants were invited and there was a 100% response rate. It was ensured that all the participant were experts in Systems Engineering and had at least a minimum of Masters degree qualification. The participants are from different fields e.g. Rail, Higher education etc. The following elements form the characteristics of the sample:

Table 10: Sampling profile

Focus group	
Age group	30 - 60
Minimum Education	Masters degree
Minimum number of years' experience in the field of Systems Engineering	At least 5

Source: Author

Except for one participant of the focus group who did not have a Masters degree and no background in Systems Engineering, all other requirements were met. This participant input and point of view was valid and important because of their experience in the TE: PDC environment. As stated in the research proposal report, the focus group was carried out because of lack of adequate information obtained from interviews. The downside of a focus group is the fact that it offers less opportunity for capturing individual perspectives (Saunders *et. al.,* (2007)). However, for this study, this was counterbalanced by interviews which were first conducted to address the individual views.

3.3 Data Reliability and Validity

For research data to be of value and use, they must be both reliable and valid. To increase confidence in the findings of the study and show the credibility of research, the following strategies were employed to ensure validity and reliability:

- Triangulation of data – multiple methods were used to collect and analyse data as explained in *section 3.2.3*.
- Results from qualitative and quantitative data were compared and integrated
- The convergence of data after interpretation proved data was valid,
- Member check
- Multiple people interviewed to observe a pattern in data collected
- Addition of focus group – after observing the lack of Systems Engineering knowledge in TE: PDC, a focus group was added as an additional instrument to supplement the information already received from interviews.
- Focus group and interviews participant were experts in their field.

3.4 Ethical Issues/Clearance

Ethics clearance was granted through the school of Mechanical, Industrial and Aeronautical Engineering. The clearance reference number is MIAEC 245/19.

CHAPTER 4

4 DATA ANALYSIS AND RESULTS

This section explores the problems uncovered, and the solutions developed through the analysis of the data from archival research as well as the interviews conducted. The failure factors deduced from the literature review were interrogated by comparing them to those identified from archival research and confirmed further through the interviews. Information from the archived company documents, as well as the interviews, was coded to better understand it. A *System Design Framework* was developed, with the *System Design Process* derived from the framework. Both the framework and process are critiqued through focus group discussion and the results discussed in chapter 5.

4.1 Analysis of the Problem Situation from Archival Research

Content analysis of archived data was performed to determine the root cause of the existing problems at TE: PDC. This included the analysis and comparison of the two processes which are currently used at Transnet namely the PDDP and the PLP, together with the documentation produced during the PDDP for one of the projects carried out by TE: PDC which will be referred to as Project X.

4.1.1 The problem situation - System hierarchy

Complex problems require holistic thinking; focusing, on the whole, gives a complete view of a complex relationship (Buede (2009)). To understand the interdependencies between TE: PDC and other systems, TE: PDC is put into a context of a larger environment showing the hierarchy of the entire system. This was also to show the context and indicate the bigger system which it is a part of i.e. show TE: PDC as a system of systems. This is achieved through the use of system hierarchy and shown by the diagram of *Figure 26*.

The following is worth noting: The highlighted onion ring shows the scope of research i.e. TE: PDC, which includes subsystems such as its employees, management, processes and facilities/equipment. The support services team is made up of Electrical Design Office (EDO) for electrical drawings, Mechanical Design office (MDO) for mechanical drawings, Bills and Routine for billing of material, Configuration for document management, and Project Management for management of projects. The request for new product/project emerges from the marketing department, which is liaised through the National Coaches management team. The designs produced by TE: PDC must abide by the standards enforced from TE Corporate affairs as well as the government regulations inclusive of the RSR.

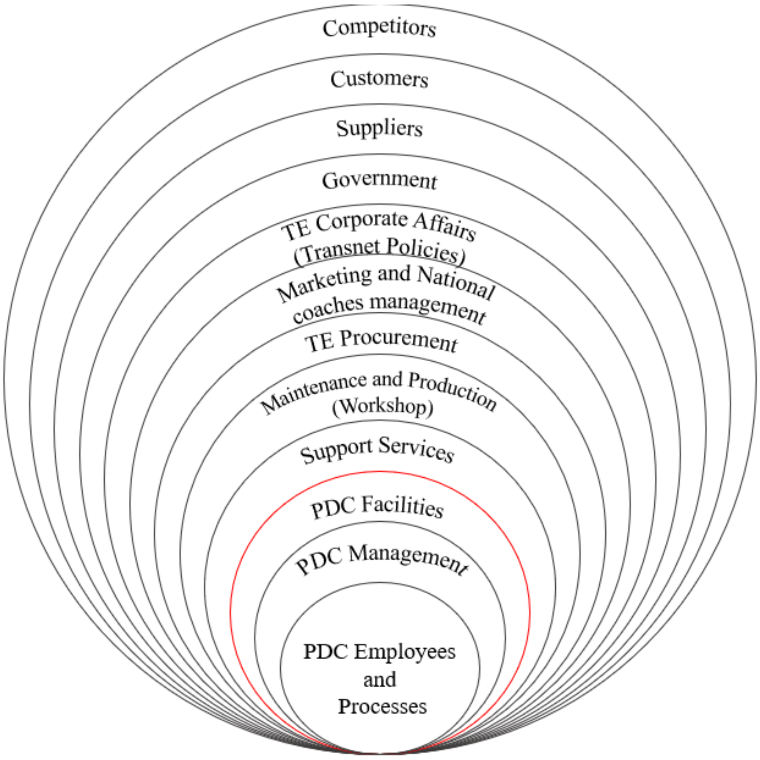

Figure 26: The TE system hierarchy
Source (Author: Adapted from the PDC PLP)

To better understand TE: PDC as a system and its boundaries, the below diagram in *Figure 27* was developed. It shows the different systems making up TE: PDC to achieve its business goals.

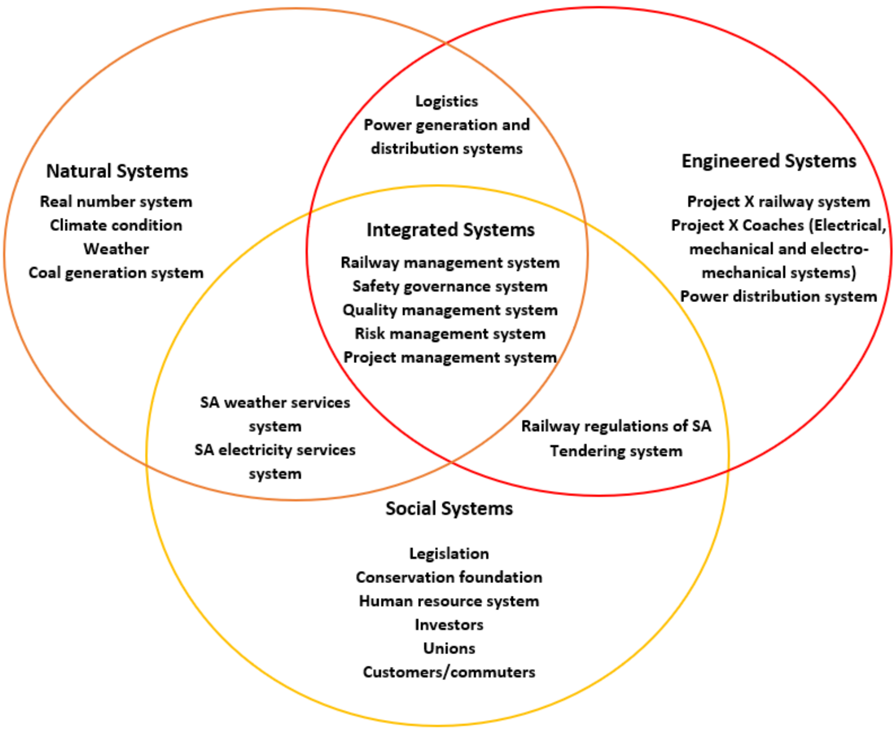

Figure 27: System boundaries of engineered system, social system and natural system for PDC as a system
Source: Author (Adapted from Adcock (2017) and multiple archived data sources)

TE: PDC as a creating system, is made from a social, natural and engineered system which interact and are integrated as above. The product produced by TE: PDC is railway passenger coaches, and the project concerned is referred to as Project X. These three systems must interact with each other to achieve the business goal. The information represented in the above diagram is used in the *System Design Framework* and the *System Design Process* to aid the process of stakeholder identification by identifying the persons responsible for each of the Integrated systems (see figure above) in each level. The different levels are explained in the sections that follow.

4.1.2 PDC PDDP vs the Transnet PLP

Two of the design processes used by Transnet are the Product Development Coaches (PDC) Product Development Process (PDDP), and the Transnet Product Lifecycle Process (PLP). The two processes were analysed to indicate their deficiencies. *Table 11* shows how the two processes follow the typical systems design methodology by mapping them with the previously identified typical system lifecycle phases. The processes were further criticised to indicate their inefficiencies.

Table 11: The PDC PDDP vs the Transnet PLP

Design and Development Phases		**Design Methodology**	
		PDC PDDP	**Transnet PLP**
Pre-Design Activities	**Establish the need**	Receive request from the marketing department from the customer request	
	Analysis of task	Establish User Requirement Specification (URS)	FEL-1 and FEL-2: Create a draft work plan
	Conceptual design	Generate conceptual ideas	FEL-1 and FEL-2: Develop a conceptual report
	Embodiment design	Develop product specifications	FEL-3: Develop feasibility report
Actual Design and Development Activities	**Detailed design**	Prepare production design drawings	FEL-4: Detailed engineering design
	Implementation	Testing and commissioning and approval, release production documents.	FEL-4 and execution: Procurement process, construction and commissioning.
Post Design and Development activities	**Use**	Out of scope	FEL-4: Hand over to operations
	Close out	Out of scope	Contractual, administration and financial closure, lesson learned document

Source: Author (Adapted from different sources as stated in the table)

From the above table, one can observe the following as flaws from the two processes:

The PDC PDDP has the following flaws:

- Designers not involved in the project initiation stages, where the system need is defined,
- Designers do not have direct interaction with customers/users, i.e. information received is secondary
- No stakeholder identification phase and requirement management processes,
- No requirement analysis to get from URS to systems requirements,
- Specifications produced for individual components are based on the URS,
- No responsible person bridging the gap between technical and managerial work,
- No involvement of post design stakeholders until the material is purchased.

The Transnet PLP has the following deficiencies:

- The process is meant for mega-projects,
- Need definition is non-existent,
- The process moves from feasibility study to detailed design,
- The process is focused on the project domain

4.1.3 Analysis of the NPD documentation for project X

The PDC archived documentation produced throughout the product development process made up of PDDP (1), User Requirement Specification (1), Project plan (1), Project X manuals (5), CAT design documents (>40), Risk register (1), tender documents (3), business plan (2), logistics plan (2), plant readiness plan (2), meeting minutes (16), quality control plan (1), project charter (1), project presentations (1), technical specification (3) etc. were analysed. The failure factors identified in *Table 5* were used as the basis for searching for evidence or traces in the different documents, to determine whether the same trends which were determined through literature indeed existed in PDC as well. The following were discovered:

Table 12: Possible design failure factors identified from archived data

Failure Factor	**Corresponding Factor No. from *Table 5***	**Evidence – Document Type**		
Not all stakeholders are involved at the start of the project	1	PDC PDDP	Meeting minutes	Logistics plan
Designers receive secondary information (As design requirements in the form of URS) as there is no interaction between customer and designers for stakeholder requirements derivation.	1, 15	Meeting minutes are from the design phase	PDC PDDP indicates the absence of designers' involvement in the project conception stage	
No translation of customer's needs to system requirement	2	No systems requirement document	Technical specification are only for components/units	PDC PDDP
Does not consider through lifecycle engineering for system design	3	Meeting minutes	Logistics and implementation planned later in the project (dates)	Plant readiness document
No verification, validation and acceptance plan	3	PDC PDDP	URS has no verification or validation plan	
Lack of config management. / No accountability	12, 15	URS	No signatures to indicate	Risk register
Incompetence in predevelopment activities	19	PDC PDDP	Risk registry not reviewed at the start of the project	
Change of scope	5	Meeting minutes	URS vs. Technical requirements documents	
Variance in cost estimation and the actual cost	18	Business plan	Meeting minutes	

All the failure factors uncovered are in support of the results from the literature review as they match with some of the failure factors identified and summarised in *Table 5* and shown in *Table 12*.

4.1.4 Statistical Analysis of Archived Company Documents: Determining the use of Systems Engineering in PDC

Coding of the archived company documents was performed using Nvivo. A word search query of all Microsoft Word and PDF documents was run using the typical lifecycle process phases/phrases and typical design phases previously identified in *section 2.2.3* and *section 2.2.2* respectively as the search words. The below bar graph resulted.

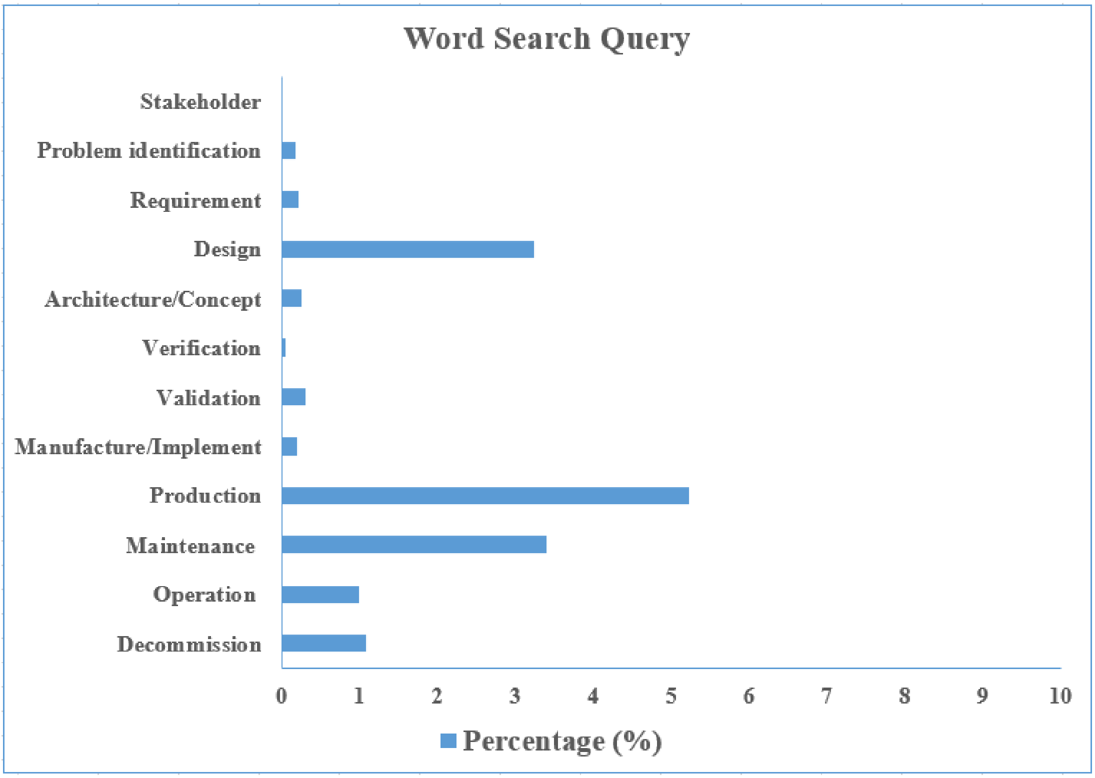

Figure 28: The words/phrases occurrence percentage in archived documents
Source: Author (From archived company documents)

The word that appeared the most in the archived documents was production at 5.22%. This may suggest that PDC is most concerned about production than design, which should be its primary focus. This was followed by maintenance at 3.41%, then design at 3.24%. There was a 0% mention of stakeholder; which confirms failure factors 1 and 15 of *Table 5*. i.e. no stakeholder identification.

4.2 Analysis of the Problem Situation Using Interviews

4.2.1 Thematic analysis of interview data

Thematic analysis of interview transcribes was performed. The below word cloud indicated the frequency of words. The most uttered word was a project which was said 119 times, then followed by design at 95. On the RHS is the top 10 words that appeared from the query.

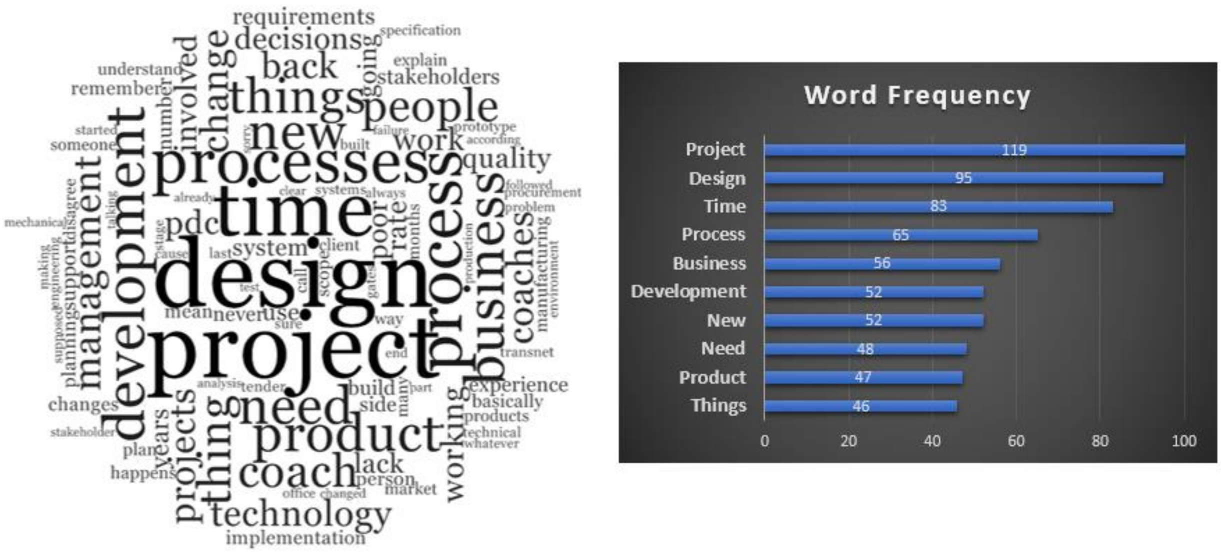

Figure 29: The word cloud and word frequency from archived document analysis
Source: Author (From multiple archived documents)

There is a gap in the usage of typical Systems Engineering terminology by the participants. This may indicate the lack of use of Systems Engineering methodologies at TE: PDC. The results are in support of the archived data analysis from the previous section.

4.2.2 The top four failure factors

The below diagram was drawn from the results of the analysis of the interview questionnaires. From the 25 failure factors identified, top five failure factors were determined to be as follow:

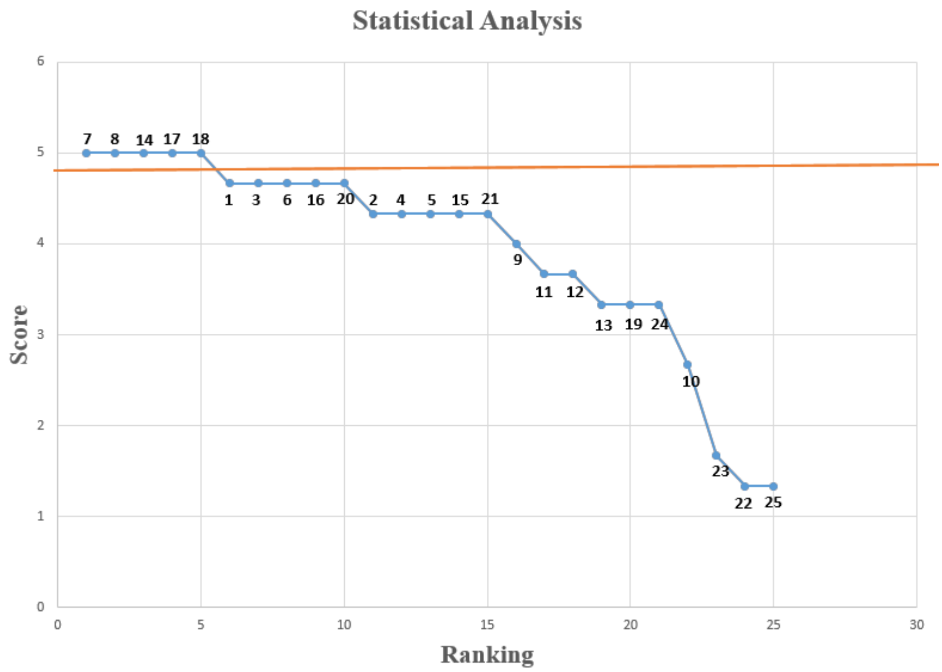

Figure 30: Cause and Effect diagram
Source: Author (From interview questionnaire)

From the above diagram, the top five design failure factors can be identified as follows.

Table 13: Top five failure factors

No.	Failure Factor
1	Poor material management (7)
2	Insufficient resources and resource allocation (8)
4	Unrealistic time frames (14)
4	Having too many projects at a time/too big of a project (17)
5	Inaccurate cost estimation/Cost overrun (18)

The following two factors were also determined (through the author's judgement) to be dominant as they were repeatedly mentioned by the interviewees.

Table 14: Top 2 additional failure factors deduced from interview analysis

No.	Failure Factor	No. of mentions
1	Adherence to processes (24)	9
2	Company procurement policies that do not favour NPD (25)	7

This makes the total failure factors derived from interviews to be seven. These seven failure factors were further interrogated using the "5 Why's" method to determine and unpack the base causes of failure. The reasoning was based on interview responses and resulted in top six failure factors as seen below.

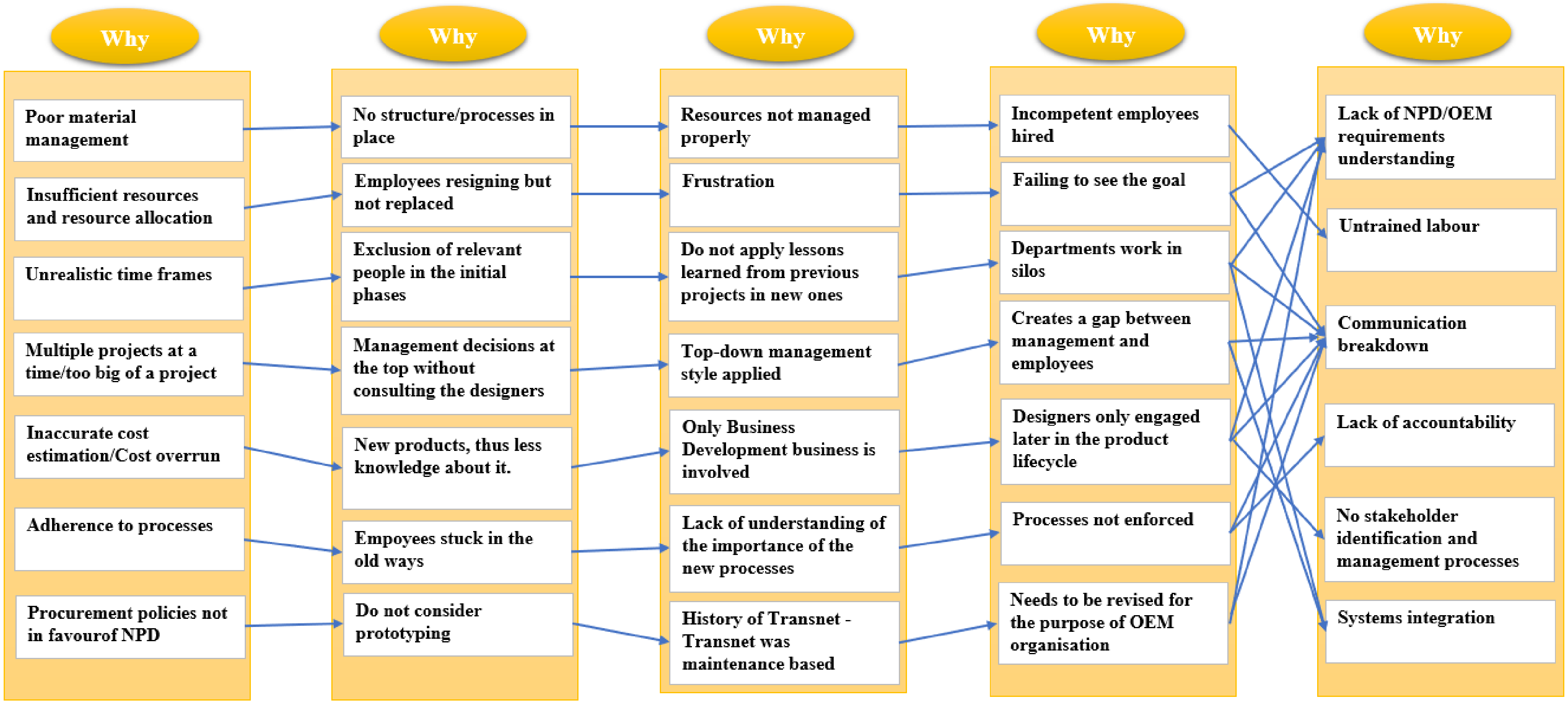

Figure 31: The top six system design failure factors in PDC as an OEM organisation
Source: Author (From interviews)

The six factors that form the basis of system design failure in PDC (based on the limited interviews) are thus:

1. Lack of understanding of what is required to be a successful NPD or OEM,
2. Unskilled or untrained labour,
3. Communication breakdown within the creating system and the supporting teams,
4. Lack of accountability within the creating system, the supporting teams, and management;
5. No stakeholder identification phase and stakeholder requirements management processes in place,
6. The integration of different systems within the creating team.

It is evident from the diagram above and the interviews conducted, that the transition of Transnet Engineering from maintenance based to OEM organisation was not carried out efficiently. Processes (e.g. Design, management and procurement) need to cater for the change.

It is important to observe the following:

- The design failure factors are made up of both soft problems as well as hard problems.
- The factor 1 and 2, need to be addressed at a higher system level/hierarch than PDC; for instance, government level, which is level 9 on the system hierarchy of *Figure 26* and is responsible for creating procurement policies to be adopted by the whole Transnet, including PDC.
- The rest of the problems i.e. failure factors 3 to 6, here on referred to as the top four failure factors, can be tacked using the *System Design Framework* and *Process* that are developed in this study.

4.3 Triangulation Results

Concurrent triangulation method was used, and the results generated from each tool were compared to solidify the design failure factors. The below diagrams show the results from each tool and colour coded according to how they are linked to one another. NB. Those left in white are not related. This diagram aims to identify similar failure factors which were identified through the three different data collection methods to ensure the validity of data.

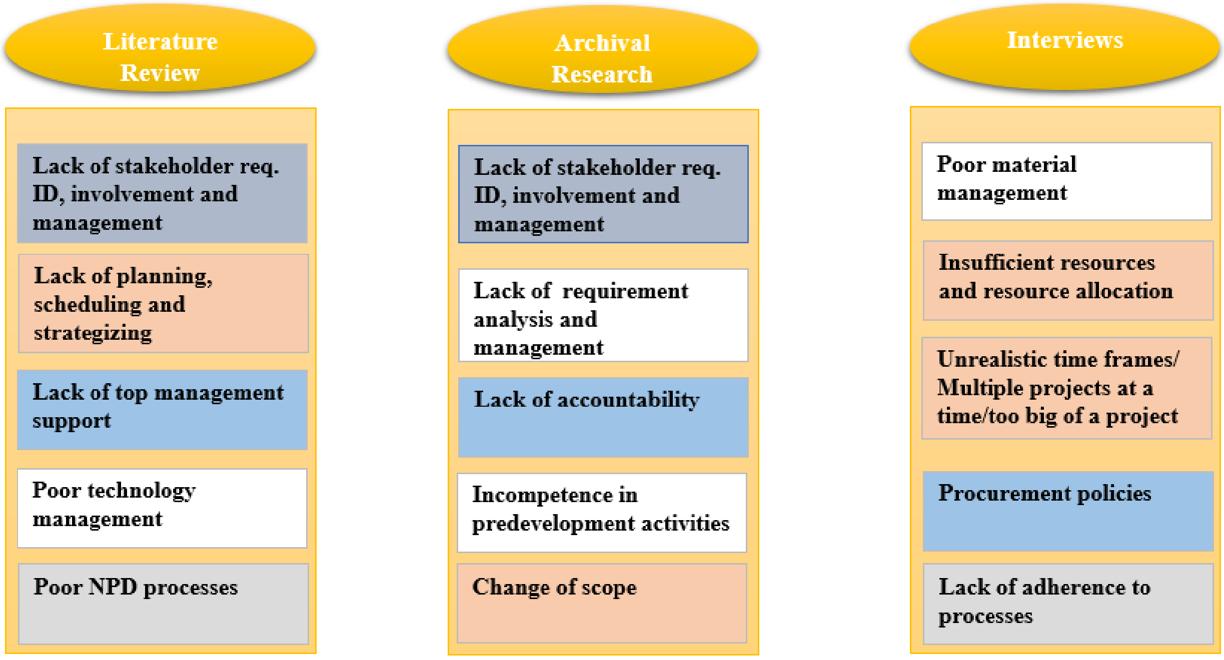

Figure 32: Relationship of the triangulation results
Source: Author

The highlighted failure factors are included in the previously identified top six failure factors (following the interrogation using the "five why's" method), which were reduced to top-four failure factors (as explained previously). The top four system design failure factors are thus:

1. Communication breakdown within the creating system and the supporting teams,
2. Lack of accountability within the creating system, the supporting teams, and management;
3. No stakeholder identification phase and stakeholder requirements management processes in place,
4. The integration of different systems within the creating team

These factors can be mitigated through the use of *System Design Framework* and *Process*.

4.4 The Development of the System Design Framework

Systems Engineering is about getting the right design, and thereafter focusing the management and enhancement of its technical integrity and complexity with good processes to the design right (Bahill *et. al*, (2009)). In short, it is about getting the right design right. This section discusses the *System Design Framework*, and the *System Design Process* developed i.e. the Systems Engineering solutions developed. Both the framework and the model were developed from combining the attributes of the following:

Table 15:Components making up the System Design Framework and model

	System Design Framework	System Design Process
Design methodologies	• Modular design method • Concurrent engineering	• Modular design method • Concurrent engineering
Lifecycle process models	• Vee model • Stage-Gate model	• Vee model • Stage-Gate model • RFS loop
Frameworks	• Zachman • COAWTET	

Source: Author

4.4.1 The System Design framework

Below is the *System Design Framework* developed from this study. The following are worth noting regarding the above framework:

- There are three levels to the framework i.e. created system, created subsystem and created component level. Thus, requirement analysis, functional analysis and design synthesis processes will cascade according to each level.
- The framework assists with the stakeholders' identification process (i.e. the WHO)
- The owner is one person. Owner is dependent on the level thus enforcing accountability
- Integrated systems are as listed in *Figure 27*.
- Transformation column refers to the transformation plan of the system at each level i.e. how will inputs be converted into outputs (outputs for each level can be observed from *Figure 33*)
- Under the Customer column: EXCO and Business development are proxy customers for TE PDC. It is thus important to establish a link to the direct users i.e. the African market, to ensure that the proxy customers' requirements are always traced back to those of the real customers.

The different parts of CONOPS (In orange) are addressed through the use of CATWOE (rearranged to COAWTET and added an element of time). The different perspectives (conceptual, logical, physical and contextual) are represented through the application of RFS model. System Analysis and Control are responsible for the management and control of Requirements Analysis, Functional Analysis and Design Synthesis phases.

Table 16: The System Design Framework

Perspective/ View	Who (Customers)	Who (Owner)	Who (Actors)	What/Why (Word-view)	How (Transformation)	Where (Environment)	When (Time)
Requirements Analysis (Conceptual)	1. African market 2. EXCO 3.Business Development	1. EXCO 2. Business Development 3. NC	PDC designers, Production, maintenance, support services, suppliers **Integrated systems	System development processes for each level (Understand what the stakeholder wants)	Use of requirement analysis tools e.g. Context diagram, states and modes analysis, parsing template etc. Verification and validation requirements/processes	1. South Africa and Africa 2. Transnet Engineering 3. Transnet Engineering and suppliers	Through lifecycle
Functional Analysis (Logical)	1. NC 2. PDC 3. PDC	1. NC 2. PDC 3. DO	PDC designers, Production, maintenance, support services **Integrated systems	Logical data modelling for each level (Understanding how the system functions)	Use of system architecture tools e.g. FFBD, DFD, C4ISR etc. Integration plan	1. Transnet 2. Transnet Engineering 3. Transnet Engineering and suppliers	Through lifecycle
Design Synthesis (Physical)	1. NC 2. PDC 3. PDC	1. NC 2. PDC 3. PDC	Designers, Supplier, RSE, workshop personnel **Integrated systems	System/Subsystem/Component design, which will meet stakeholder requirements	Use of COTS modelling and simulation tools e.g. CAD	1. Transnet Engineering 2. Transnet Engineering 3. Workshops, suppliers	Through lifecycle
System Analysis and Control (Context)	External company	NC	Owner of each stage and level of design	Project and business management	Management of: Information, Risk, Configuration, Resources, Finances, Ownership/Responsibilities	Gate review meetings	Gate reviews

*Source: Author (**refer to Figure 27 for explanation)*

4.4.2 The Systems Design model

The model is made up of levels, with each level consisting of its own RFS loop i.e. iteration process. Thus, requirements are defined and classified at each level. Each phase/stage has a gate/review with a downstream representation to allow the continuation of the master design and enable planning processes to be in place and occur concurrently for other downstream activities.
To be able to fully execute the above *System Design Process*, an understanding of the Systems Engineering competency as described in *section 2.4.1* is needed. The model incorporates business, product and system management principles to ensure design success from multiple viewpoints.

The Stakeholder Requirement Specification document is one of the inputs to system design phase/process, which will continue by eliciting System Requirements from the Stakeholder Requirements; but first analysing the received Stakeholder Requirements to make sure that they meet the criteria of the quality requirement (i.e. *Figure 15*) and can be traced back to the stakeholder needs. This is one of the prerequisites of the first stage gate review to pass.

There are four stage gate reviews in the *System Design Process*. It is important to state the prerequisites for each stage review at the beginning of the project as part of the planning process. Alongside the stage-gate design outputs, there should be an alignment with the critical commercial gates approval (administered through the Business Development and Finance departments) which are organisational specific. It is important to outline from the start of the project, the expected commercial and financial outputs of each stage gate.

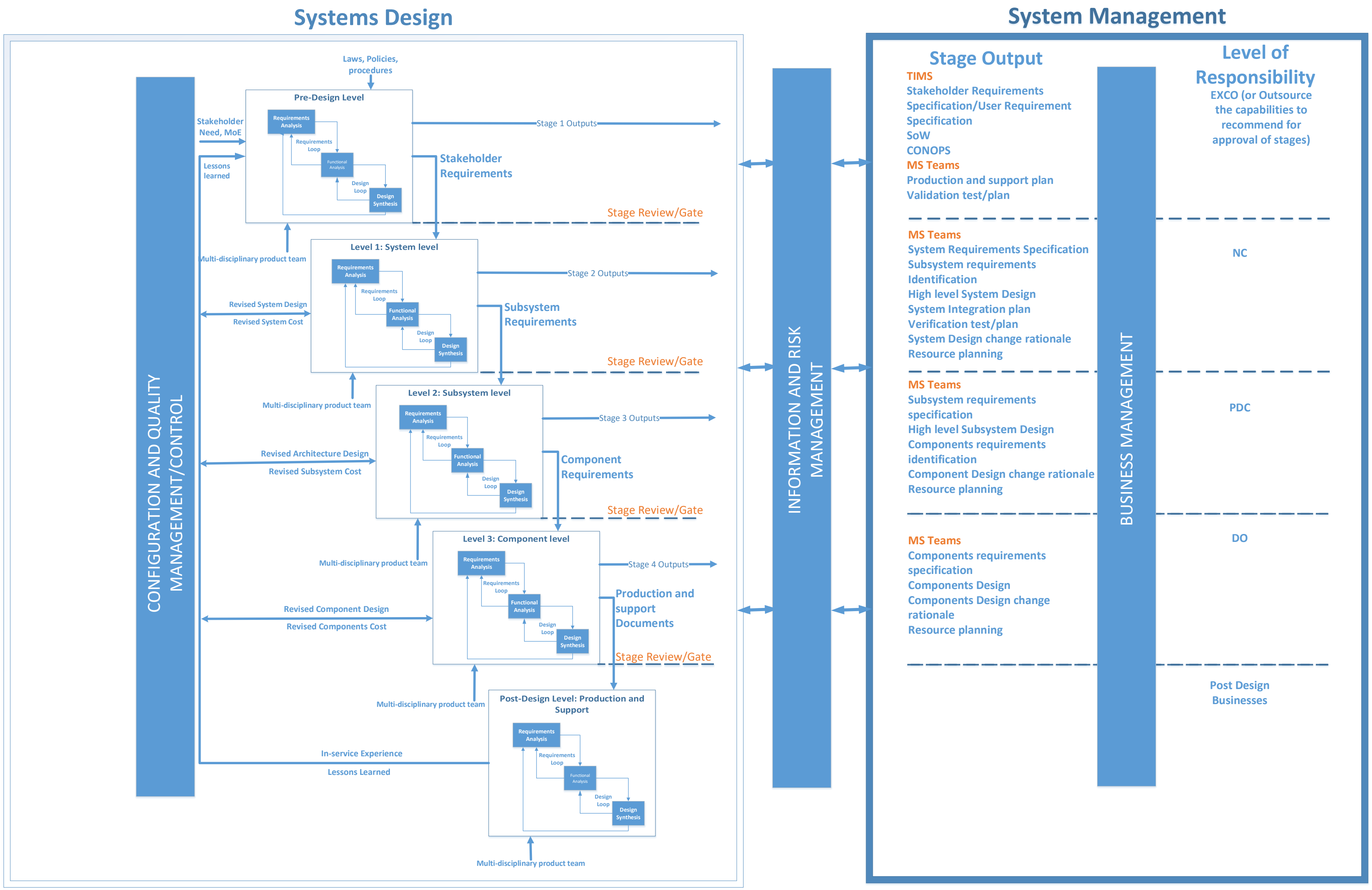

Figure 33: The System Design Process. Source: Author (Adapted from multiple sources)

CHAPTER 5

5 DISCUSSION AND RECOMMENDATION

5.1 The System Design Framework and System Design Process Discussion

This section discusses how the developed framework and model addresses the failure factors which were identified through the study (i.e. *Section 4.2.2*).

The framework and process are believed to be efficient because;

- they focus on large scale organisational and management of design and development, which PDC is known for, given the types of models which it was derived from.
- they consider the interaction design and development processes by applying the RFS loop to every level and using the feedback loop to interact to other levels.
- they emphasise on the decomposition of complex problem and design into subsystems, whose solutions are developed, verified and validated individually at every level of the subsystem abstraction/hierarchy; and then integrated into a single system. This is indicated through the use of the Vee model as well as concurrent engineering, and decomposition of levels.
- they use formal structured reviews to ensure that a phase of the design process is properly executed, and the design is sufficiently matured before proceeding to the next phase/iteration/abstraction of the design/design process.
- they ensure proper definition, flow-down and control of requirements and addresses segregation of the subsystems through requirements definition, analysis and management as well as a SEMP.
- they plan for Validation and Verification through the application of the Vee model.
- they consider the left-shift effect:
    - Addresses and prepares for upcoming product development phases through the use of DFX.
- the feedback channels are consciously developed, managed and monitored for design changes and implementation.
- multifunctional teams are defined and their interactions (let it be through the progress of design, correct problem definition, changes implementations or coordination of processes), and needs to be managed.
- roles are defined, and resources managed at every phase.
- the *System Design Framework* encourages stakeholder requirements identification and involvement, enforces accountability and promotes predevelopment activities to complete the loop.

5.2 The Focus Group Discussion

A focus group was conducted to analyse the results found through research. The aim of the focus group was as follow:

- To determine whether the research methodology used was sufficient to deduce the findings,
- To determine whether the *System Design Framework* and the *System Design Process* developed addresses the top four failure factors identified.
- To determine how can the framework and process be improved?

The following were the outcome of the focus group.

5.2.1 Analysis and critique of the System Design framework and process

The following applies to the study in general:

The key outcome from the focus group discussion was the limitation which was brought by the scope constraints. The scope of the study was only limited to the design phase and TE: PDC as the SoI. This brought limitations because:

- It is difficult to consider design in isolation. Some of the "design failures" which were identified from data analysis are predesign problems which were carried through to design phase.
- It cannot be assumed that the predesign phase of system lifecycle was executed correctly and the input to the design phase is ideal, as proven through interviews.
- Problems identified were from the point of view of TE: PDC, which works closely with other businesses whose views were not represented.

It was also noted that Systems Engineering Competencies documented through INCOSE_UK (2015) apply to a Systems Engineer (the person) thus, does not contain elements such as culture, reliability, availability and safety. However, it does state in INCOSE_UK (2015) that "*the systems engineering competency framework is generic in purpose… It can be applied in the context of an organisation, a project, an individual and/or a training program.*"; thus, qualifying the framework to be used in this context.

The following applies to just the System Design Process:

According to the focus group participants, it was difficult to judge/contrast and compare the processes if the newly developed process is an improvement from the one currently used without physically seeing the currently used process. The current process could not be shared with the participants as it is company Intellectual Property (IP). However, the following was said regarding the newly developed process:

- Lifecycle model must start with the business problem/situational analysis, and not with the solution domain (i.e. design phase) to understand the problem and solve for the correct problem. However, this risk is reduced (or mitigated) in the *System Design Process* by introducing the requirement analysis loop of the RFS model, to analyse the inputs to design phase (i.e. Stakeholder Requirements) and by introducing feedback to pre-design phase (requirement validation) to ensure that the correct problem is being solved for.

No further failure factors came out of the focus group discussion. It was also demonstrated how each of the top four failure factors was addressed by both the framework and the process. Further comments from the focus group are summarised in Appendix C, together with the actions taken to implement them.

5.3 Recommendations

Taking into consideration the above findings, the following recommendations are made by the author for the application of the *System Design Framework* and *Process* to be a success:
for the application of the *System Design Framework* and Model to be a success:

- Transnet Engineering and its employees need to understand further what New Product Development entails and what being an Original Equipment Manufacturer requires in terms of their processes and policies.

The typical NPD process was discussed in *section 2.2.2* using the Booz Allen Hamilton model. This process was further compared to the typical maintenance information flow/procedure (RHS of *Figure 34*) to map the differences. The two processes, together with their differences are summarised in the below:

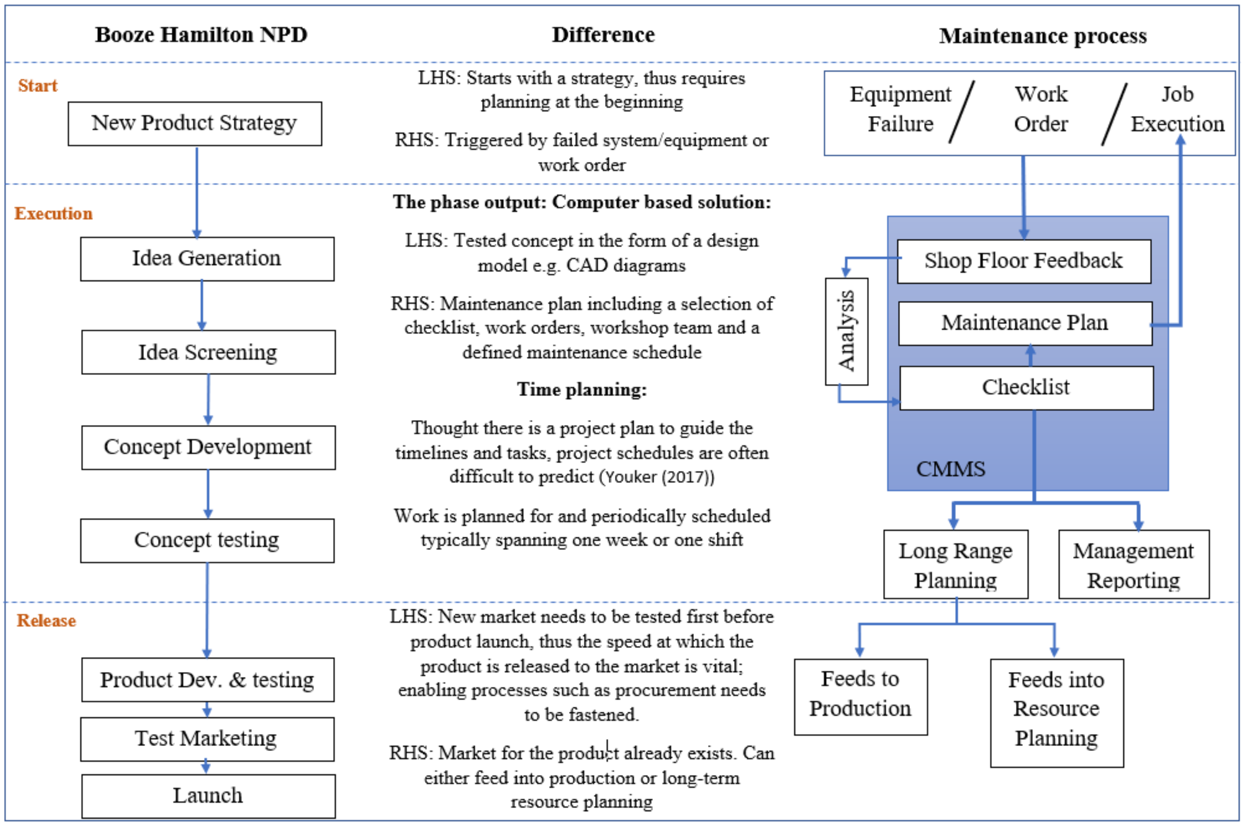

Figure 34: The difference between NPD and Maintenance processes
Source: Author (Adapted from Kundu (2015) and Porrill (2020))

According to the interview participants, procurement policies and processes were identified as one of the processes which delay the product development process. Transnet has developed a Procurement Procedure Manual (PPM) which was derived from the Public Finance Management Act No. 1 of 1999 (PFMA (2010)). This document establishes the framework with which Transnet shall conduct all procurement activities. The process stated in the manual prohibits designers from direct contact with suppliers. This is to prevent any financial misconduct or favouritism towards suppliers. However, the process makes it difficult for designers to obtain excess information which may be required to further their design and the process usually tends to be prolonged. Transnet Engineering needs to understand the difference between the NPD and maintenance processes in order to customise the processes (such as procurement processes) accordingly and allocate resources as needed. Processes that facilitate the execution of procurement policies such as the Public Finance Management Act (PFMA) (1999), should be customised to better suit the type of organisation in hand.

- Although Transnet Engineering is already transitioning into an OEM organisation, a plan needs to be put in place as to how to also transform the behaviour and mindset of its employees. Training needs to be provided as well.

The following recommendations were from the focus group. The researcher's response and actions taken are also presented:

- The research scope should be broadened to include the predesign stages.
    - The study was limited to the design phase and TE: PDC as an SoI to limit the scope of the research as the degree pursued is 50% course work and 50% research, thus the scope had to be restricted. It is however agreed that broadening the scope would bring additional value to the research.
- Some of the identified design failure factors of *Table 5* are too general and should be revised to better suit the context (i.e. Design context), or the scope should be broadened.
    - The following were changed by the researcher:

Table 17: Changes made to the top 20 system design failure factors

Current design failure factor:	**Changed to:**
Poor material management	Poor configuration management.
New product development speed	Delayed design release

- The views and contribution of other businesses which work closely with PDC can be represented as inputs to the *System Design Process*.
    - This recommendation was applied. Furthermore, a stage-gate review is recommended to ensure that the inputs to the design phase are correct.
- The Systems Engineering competency framework should be tailored to include other elements such as culture, reliability, availability and safety.
- The situational analysis (i.e. AS-IS framework and process) should be represented, as well as the TO-BE (required stage) so that the transition is visible.
    - Below is the simplified PDC Design Process (AS-IS). The original process includes processes from other supporting and managing teams, which are represented as inputs or outputs to simplify the representation of the process and to protect the document confidentiality.

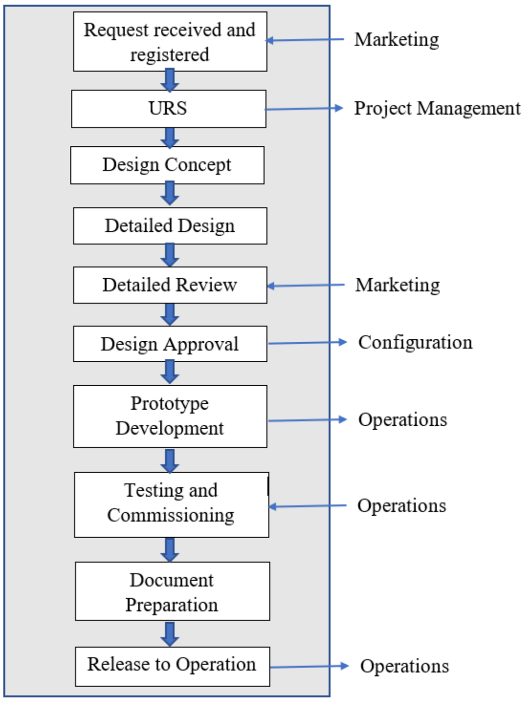

Figure 35: The PDC PDDP
Source: Author (Adapted from the PDC PDDP)

In addition to the process cons listed in *section 5.1* and the difference in the organisational structure listed in *Table 1*, some of the major differences between the AS-IS (above) and TO-BE, *Table 16*, situation:

Table 18: PDDP (AS-IS) vs. System Design Process (TO-BE)

AS-IS	TO-BE
No stage gates	Stage gates present; encouraging accountability through enforced document and tasks sign-offs and a clear indication of the responsible personnel
No feedback/lesson learned (Waterfall method)	Has feedback loop for each level and lessons learned at project initialisation phase (Uses best practices from a combination of multiple design methodologies)
Not all stakeholders are involved from the beginning of the project e.g. Config. And Operations personnel are brought in later in the system lifecycle	Has stakeholder identification stage and a framework to assist with the process
No requirements analysis process. The process moves from URS development to concept design	Requirements are analysed at each level (i.e. system, subsystem, component) to ensure that the corrects inputs are accepted into each level.
Does not plan for the downstream phases such as production and maintenance, at the beginning of the project	There is a left shift through the validation, verification and integration planning as well as the resource planning for the level that follows.

- The use of computerised Model-Based Systems Engineering (MBSE) tools should be investigated as an alternative to mitigating design failures.
    - The research aimed to develop a framework and process. The option of MBSE can be investigated as an alternative to the *System Design Framework* and *System Design Process*.

Further recommendations were made from the focus group and were implemented into the research and report. Appendix C summarises these recommendations as well as actions taken in the research/report to address their recommendations.

CHAPTER 6

6 CONCLUSION

6.1 Summary of Study

The research represents the solution space i.e. design phase. However, it has proven to be challenging to isolate the issues of the design phase from the pre-design phase problems, which has been identified as the problem space. As a result, some of the top four failure factors apply to the predesign phase e.g. *Failure Factor number 3:* No stakeholder requirements identification phase and stakeholder management processes in place.

The design phase was chosen by the researcher because it is the space where TE: PDC is concerned with. However, this has proven by the study to be deficient as problems from the pre-design phase are carried through to the design phase, increasing the chances of solving for the incorrect problem. Thus, TE: PDC must also be involved or represented in the problem space, and work together with the business responsible for eliciting the stakeholder needs and the Stakeholder Requirements. To attempt to cancel this effect it was suggested to include the "acceptance of Pre-Design Phase outputs process" at the first stage review as one of the prerequisites to be satisfied before the commencement of the Design Phase.

The *System Design Framework* used Systems Engineering concepts to address the failure factors identified. They were applied as follows:

Table 19: Design failure factors and SE concepts used in the System Design Framework and/or Process to mitigate each

Design failure factor	Systems Engineering concept applied
1. Communication breakdown within the creating system and the supporting teams,	Stakeholder engagement, Requirements analysis, The use of Microsoft Teams platform/Tool
2. Lack of accountability within the creating system, the supporting teams, and management	Stage gate reviews Apply Baseline Management
3. No stakeholder identification phase and stakeholder requirements management processes in place	Use of COAWTET (CAO part assist with stakeholder identification) and the configuration management platform
4. The integration of different systems within the creating team	Integration plan as one of the outputs of design phase in the design process. Appoint a Project Systems Engineer to apply SEMP as a tool

Source: Author

6.2 Limitations of the study and further research

The following were the limitations of the study, and could be further explored by those involved in similar studies:

- The scope of the research was limited to the design phase and only to the TE: PDC team. This leads to the following potential shortcomings:
    - The possibility of inheriting failure factor from pre-design phases which are not addressed by the study,
    - Not considering the influence of other teams which work closely with TE: PDC and have a direct influence on their processes. These additional team members could also be used as interview participants to increase the sample size and obtain better accurate results in any further research taken in similar studies.
- Treat design and development as one. This study has proven the difficulty of separating the two phases, especially for an entity such as TE: PDC as the two are mutually exclusive. For further research, the study should also include the development phase where prototyping is included as part of the study as it is also one of TE: PDC's expected outputs.

The above suggestions could yield better results should they be followed.

6.3 Conclusion

The *System Design Framework* along with the *System Design Process* were developed based on the outcome of the analysis of data from archived data and semi-structured interviews, as well as findings of the critical literature review. Both the *System Design Framework* along with the *System Design Process* were further interrogated and verified through a focus group session.

The research objectives can be restated as follows:

- Evaluate factors affecting the performance of OEM design projects throughout the lifecycle.
- Develop a *System Design Framework* for the development of coaches in TE as an OEM.
- Verify the use of the framework to develop the final *System Design Framework*.

Through following the concurrent triangulation method which included the quantitative archived data, and qualitative semi-structured interviews and focus group, the above-mentioned objectives were met and a verified *System Design Framework* was produced as a result. The *System Design Framework and Process* also demonstrate the ability to consider a holistic lifecycle by showing an understanding to solve a problem in all levels that design operates in, this includes levels from requirement analysis to production and support; meeting the purpose of the study as stated in *section 1.2*.

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APPENDIX A: INTERVIEW TEMPLATES

Transnet Engineering (TE) Product Development Coaches (PDC) Designers Interview Questions:

1. The sheet provided is a list of factors identified from the literature review as the major causes of system design failure in New Product Development. Using your experience, on the scale of 1 to 5 (1 being strongly disagree and 5 being strongly agree), rate each individual factor. Explain why you rated them as you did.
2. Are there any other system design factors you can identify that are known to be the causes of failure in a system which do not appear in the first table? Also, rate them as above.
3. Of all the above-rated factors, which would you consider being the top 5 most contributing factors to system design failure? And why them?
4. Focusing on TE's transition from being maintenance to OEM organization, how would you say the design process has changed to accommodate the transformation?
5. Explain how the current design process used takes into consideration all system lifecycle process phases.
6. Explain how the current design process involve and communicate with the project stakeholders when making decisions?
7. Was the transition from maintenance to OEM organization planned for in terms of change in processes and introducing them to the employees of PDC? If yes, how? If No, what measures were taken to address change?
8. On average, how much of the project time (In percentage) is allocated to the following typical product development lifecycle phases:

Lifecycle phase	**Percentage**
Planning	
Stakeholder analysis	
Requirements analysis	
Conceptualization	
Detailed design	
Implementation	
Testing	
Validation and Verification	
Manufacturing	

9. Which Systems Engineering processes/practices does your department follow? And how effective is it?

10. If none, how would applying Systems Engineering practices to your project problem-solving change the way you solve problems?

Transnet Engineering (TE) Product Development Coaches (PDC) Designers Interview Questionnaire:

1. Please rate your agreement of the following factors as the major causes of system design failure.

   Place a cross (X) in the appropriate box.

Failure factor		Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
1.1.	Lack of stakeholder involvement and management leading to communication breakdown	1	2	3	4	5
1.2.	Lack of requirements management including poorly defined requirements, incomplete specification documents and poor specification change management	1	2	3	4	5
1.3.	Lack of planning, scheduling and strategizing	1	2	3	4	5
1.4.	New product development speed	1	2	3	4	5
1.5.	Unclear scope and goals leading to scope creep.	1	2	3	4	5
1.6.	Rework due to change of scope and frequent design changes due to errors	1	2	3	4	5
1.7.	Poor of material management	1	2	3	4	5
1.8.	Insufficient resources and resource allocation (unidentified roles and responsibilities)	1	2	3	4	5
1.9.	Lack of top management support	1	2	3	4	5
1.10.	Technology management/ Immature technology/ Poor Technology Readiness Level identification	1	2	3	4	5
1.11.	Poor New Product Development processes	1	2	3	4	5
1.12.	Poor quality control processes (monitoring and tracking processes)	1	2	3	4	5
1.13.	Lack of technical and/or market knowledge and experience	1	2	3	4	5
1.14.	Unrealistic time frames	1	2	3	4	5

1.15.	Poor Internal/External communication	1	2	3	4	5
1.16.	Interdependencies in cross functional teams not identified resulting in poor integration process	1	2	3	4	5
1.17.	Having too many projects at a time / too large of a project	1	2	3	4	5
1.18.	Inaccurate cost estimates/ Costs overrun	1	2	3	4	5
1.19.	Proficiency in predevelopment activities (preliminary technical assessment, preliminary business/financial analysis, discussion of lesson learned from previous projects)	1	2	3	4	5
1.20.	Hostile organizational environment / social environment	1	2	3	4	5

2. Add your own additional failure factors and rate them as above.

Failure factor		**Strongly disagree**	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**
1.21.		1	2	3	4	5
1.22.		1	2	3	4	5
1.23.		1	2	3	4	5
1.24.		1	2	3	4	5
1.25		1	2	3	4	5

APPENDIX B: FOCUS GROUP QUESTIONS

Focus group questions: Systems Engineering experts (TCSE and Transnet)

1. The interviewer will give a presentation on the *System Design Framework* developed.
   - Using your expertise, critique the framework.

2. The designer present the top 10 New Product Development failure factors obtained from literature review, content analysis of the company archived data and the Transnet Engineering (TE), Product Development Coaches (PDC) interviews.
   - Which failure factor do you think the presented *System Design Framework* would not be able to address and why?

APPENDIX C: FOCUS GROUP COMMENTS

There were six participants in total. The comments from each of the focus group participants are summarised in the below table:

Table 20: Focus Group comments and actions taken

Participant No.	Comment	Action taken
1	Need to define what a "system" is in the context of this study. A definite distinction between the created and creating system must be made.	Terminology defined in *section 2.2*.
1	The use of Systems Engineering competency framework in this context of a "system" is invalid as the SE competency were meant to evaluate a Systems Engineer, the person not the system. Hence it does not include other factors like culture.	Systems Engineering competency framework can be applied not only for persons, but also for organisations and systems. Suggestion made in *section 5.2.1.*
2	Define what is meant by system design.	Done is *section 2.2*.
3	The design failure factors resemble the critical success factors as known from literature. They need to be reworded to suit the context of use i.e. design	The design failure factors were drawn from the critical success factors. However, they cannot be reworded for this study as they have already been used to obtain data from interviews. Recommendation is made in *section 5.3.*
1	This study and the developed system design process needs to represent a problem from business problem stage not from the development of the solution i.e. design.	Recommendation was made is *section 5.3.*
4	The scope of the research (TE:PDC as the SoI and Design as the phase of focus) brings a lot of restrictions to the study.	For the purpose of the academic study, scope had to be set and abided to because of the type of MSc (i.e. 50/50).

2	It is impossible to isolate design issues from the predesign phases.	The focus was on the design phase. However, the effect of the predesign phase was recognised and brought through the inclusion of the Systems Engineering Competency framework.
4	If it is assumed that the o predesign phases were executed efficiently, then their outputs should be stated and fed to the design phase.	This is explained in *section 2.4.1.2* and demonstrated by the system design process in *section 4.4.2.*
2	Define what is meant by framework in the context of the study.	*Section 2.4.2* explains this.
2	The risk of solving for the wrong problem (Since the systems design process is focused on the design phase which is solution based) can be mitigated by analysing the inputs to the design phase	This is already applied by the use of the abstracted RFS loop/model. See *section 2.4.2.*
3	Organisational approval stages need to be represented in the stage gates.	This needs to be further researched. Recommendation is made in *section 5.3.*
5	Define what is meant by each level on the framework and process.	Done. See *section 4.4.*
1	Design should not be viewed as a phase but rather as process that occur throughout the lifecycle of the system.	Noted.
4	The process should include lessons learned at the beginning of each project.	The process consists of feedback loops which also ensures that the last phase feeds back to the first phase as lessons learned. See *section 2.4.2.*
3	There should be a representation of the framework's and process' AS-IS along with the Should-Be state, to indicate the transformation of the organisation.	Recommendation is made in *section 5.3.*

1	CATWOE looks at the requirements determination system, hence the need to show the system hierarchy for each level.	This is met by explaining the different systems level.
1, 2, 3, 4	It is difficult to contrast and compare the developed system design process if the currently used design process for PDC cannot be shared with the panel.	The process used by PDC cannot be shared with external candidates as it is confidential and regarded to be company Intellectual Property.
5	Would like to apply the framework on the project they are busy with.	The document can be shared with the participants.
6	Recommendation should be made for future researchers to consider a broader scope than design and SoI as beyond PDC.	Recommendation is made in *section 5.3.*

APPENDIX D: ACRONYMS LIST

Table 21: Acronyms

Acronym	Meaning
ADDIE	Analysis Design Development Implementation and Evaluation
BAH	Booz Allen Hamilton
INCOSE	INternational Council of Systems Engineering
CATWOE	Customers, Actors, Transformation, World-view, Owners and Environment
COAWTET	Customers, Owners, Actors, World-view, Transformation, Environment and Time
CMMS	Computerized Maintenance Management System
CONOPS	CONcept of OPerationS
DO	Design Office
DSM	Design Structure Matrix
EDO	Electrical Design office
EDO	Electrical Design office
FMEA	Failure Mode and Effect Analysis
ICOM	Inputs, Constraints, Outputs and Mechanisms
IDEF	Integrated Definition for Function modelling
ICAM	Integrated Computer Aided Manufacturing
MDO	Mechanical Design office
MMF	Maintenance Management Function
MS	Microsoft
NC	National Coaches
NPD	New Product Development
OD	Operating Division
OEM	Original Equipment Manufacturer
PD	Product Development
PDC	Product Development Coaches
PDDP	Product Design and Development
PFMA	Public Finance Management Act
PLP	Project Lifecycle Process
PM	Project Management
RFS	Requirement analysis, Functional analysis and allocation, and design Synthesis
SEM	Systems Engineering Management
SEMP	Systems Engineering Management Plan

SoI	System of Interest
SSM	Soft Systems Methodology
TCP	Transnet Capital Projects
TCSE	Transnet Centre of Systems Engineering
TE	Transnet Engineering
TIMS	Transnet Integrated Management System
TQM	Total Quality Management
VSM	Viable System Model
WBS	Work Breakdown Structure